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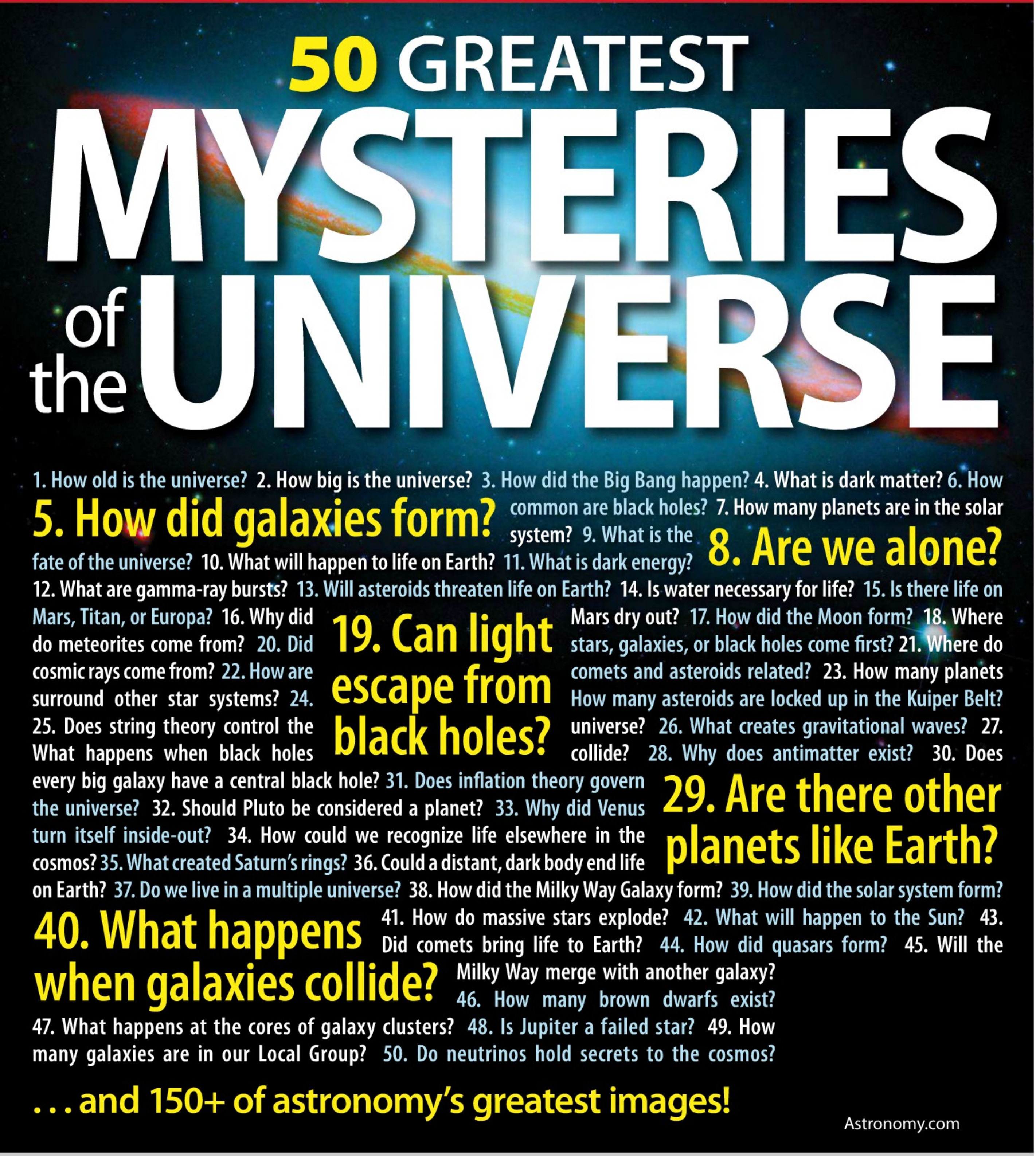

50 GREATEST MYSTERIES of the UNIVERSE

1. How old is the universe? 2. How big is the universe? 3. How did the Big Bang happen? 4. What is dark matter?

5. How did galaxies form?

6. How common are black holes? 7. How many planets are in the solar system?

8. Are we alone?

9. What is the fate of the universe? 10. What will happen to life on Earth? 11. What is dark energy? 12. What are gamma-ray bursts? 13. Will asteroids threaten life on Earth? 14. Is water necessary for life? 15. Is there life on Mars, Titan, or Europa? 16. Why did Mars dry out? 17. How did the Moon form? 18. Where do meteorites come from?

19. Can light escape from black holes?

20. Did stars, galaxies, or black holes come first? 21. Where do cosmic rays come from? 22. How are comets and asteroids related? 23. How many planets surround other star systems? 24. How many asteroids are locked up in the Kuiper Belt? 25. Does string theory control the universe? 26. What creates gravitational waves? 27. What happens when black holes collide? 28. Why does antimatter exist?

29. Are there other planets like Earth?

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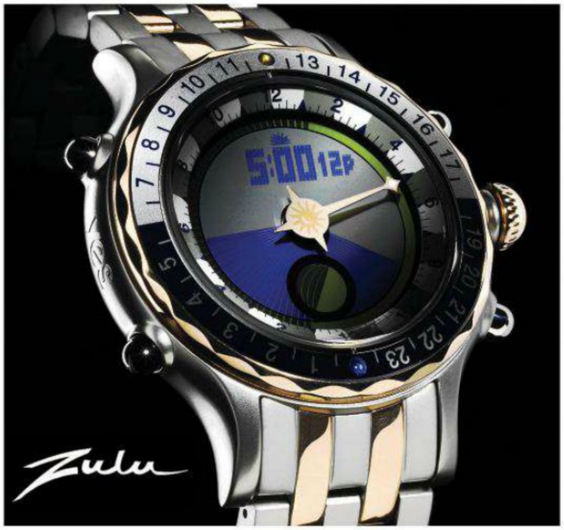

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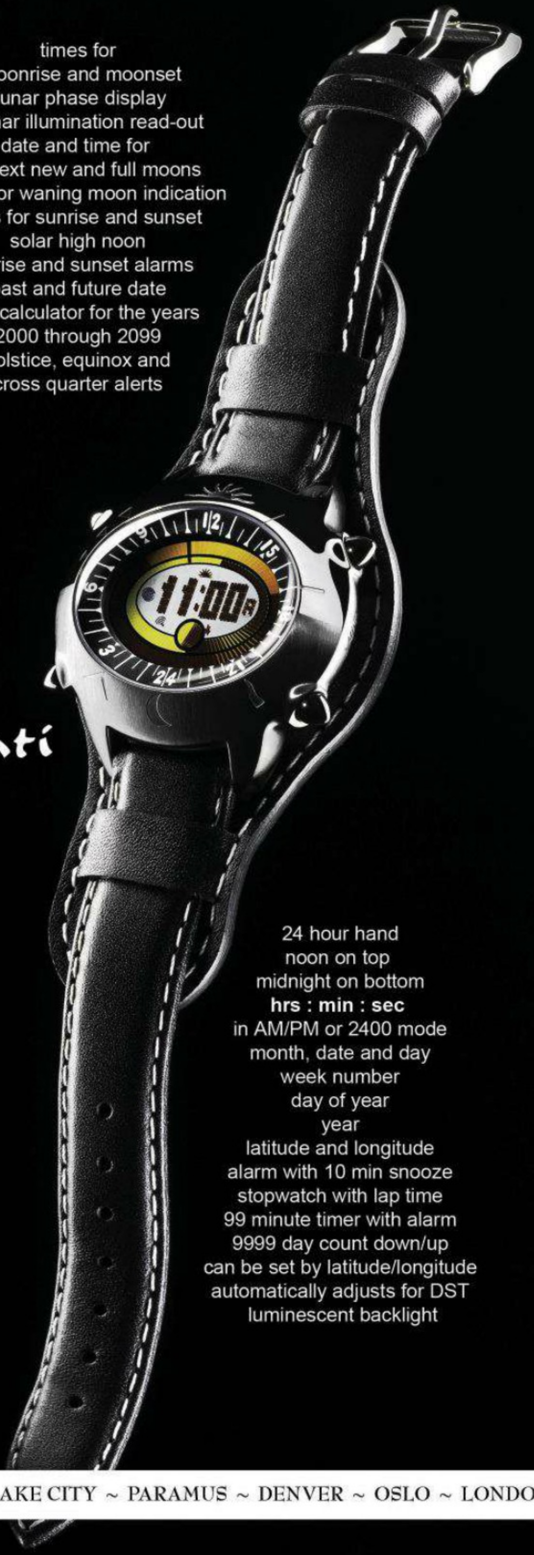

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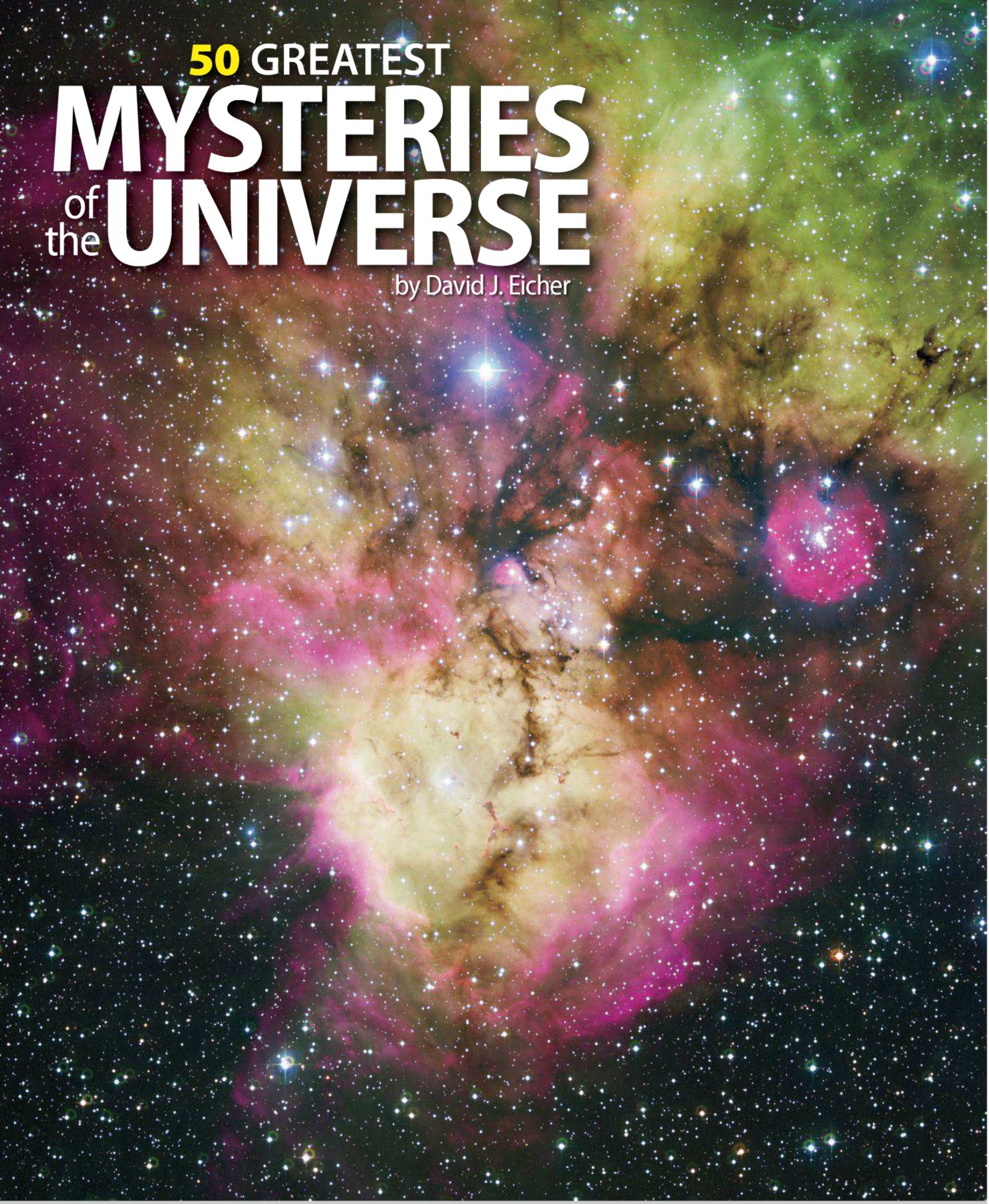
50 GREATEST MYSTERIES of the UNIVERSE

by David J. Eicher



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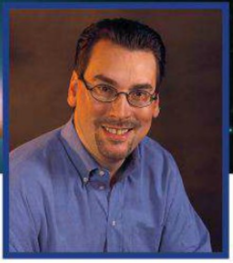
BEAUTIFUL UNIVERSE. **Colorful gas and dust clouds envelop the star cluster NGC 2467 in the southern constellation Puppis.** ESO



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A **universe** of **limitless wonder**

We live in interesting times. Look at the first 100,000 years of modern humans on the planet: You have a long struggle to find food and shelter, followed by 5,000 years of early civilization and city-building, followed by technology giving us a mature understanding of the cosmos just in the last century. That's pretty incredible stuff. Given the fact that modern humans have been around for 5,000 generations, that we're just getting to know the basic story of the universe and how it came to be is mind-boggling.

Drawing on *Astronomy* magazine's long heritage as the leading publication in its field, *50 Greatest mysteries of the universe* explores the cosmos' biggest questions — the first publication to do so. As with all complex scientific questions, some answers are completely known, others are generally understood, and the remainder aren't known. We're just starting to see where the questions might take us — without the rich details that will come down the road.

The first few questions are the heavyweights, like: How old is the universe? How large? What started the cosmos? How did galaxies form? Are we alone? What will ultimately become of life on Earth?

Many of these questions — although in somewhat different forms — undoubtedly darted through early humans' minds as they gazed skyward. Looking toward a heaven full of twinkling lights, they probably pondered what they were viewing and why they inhabited this rocky little world.

These big questions are answered only in part, and some haven't yet been answered. And then come finer questions of the cosmos — questions unimaginable until recent times: What are gamma-ray bursts? Why did Mars dry out? Can light escape from black holes? Where do cosmic rays come from? Does string theory control the universe? What creates gravitational waves?

After reading this special issue, you will not have all the answers. Like all sciences, astronomy is a work-in-progress, one that moves along toward understanding a little at a time, bit by bit. But you will have many of the answers, and you will perceive the questions and the astronomers' work more clearly than before. As an astronomy enthusiast, whether you're an active observer or an armchair reader, you'll have a much deeper understanding of where astronomy stands.

Perhaps, most importantly, you'll have fun with the subject. At the next cocktail party, you'll have great conversation starters. Among others interested in the universe, you'll hold sway with a vault of knowledge. When the subject comes up at an astronomy-club meeting, you can chime in about high-energy particles, cosmic inflation, why Venus turned itself inside-out, and how Saturn's rings formed. That's really the most satisfying part of this hobby: enjoying the quest for knowledge, placing what we see around us into some kind of meaningful context.

After your investment in this relaxing, interesting reading, you'll enjoy a greater perspective about the deep, dark universe surrounding us.

Yours truly,

David J. Eicher

50 GREATEST MYSTERIES of the UNIVERSE
COLLECTOR'S EDITION - 2007

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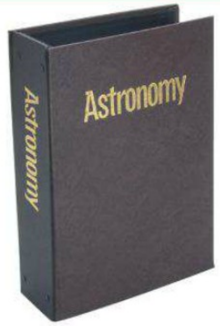

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1

How **old** is the **universe?**

Over the past century, astronomers have deduced several ways to estimate the age of the universe. At the dawn of this century, the universe's age remained far from certain.

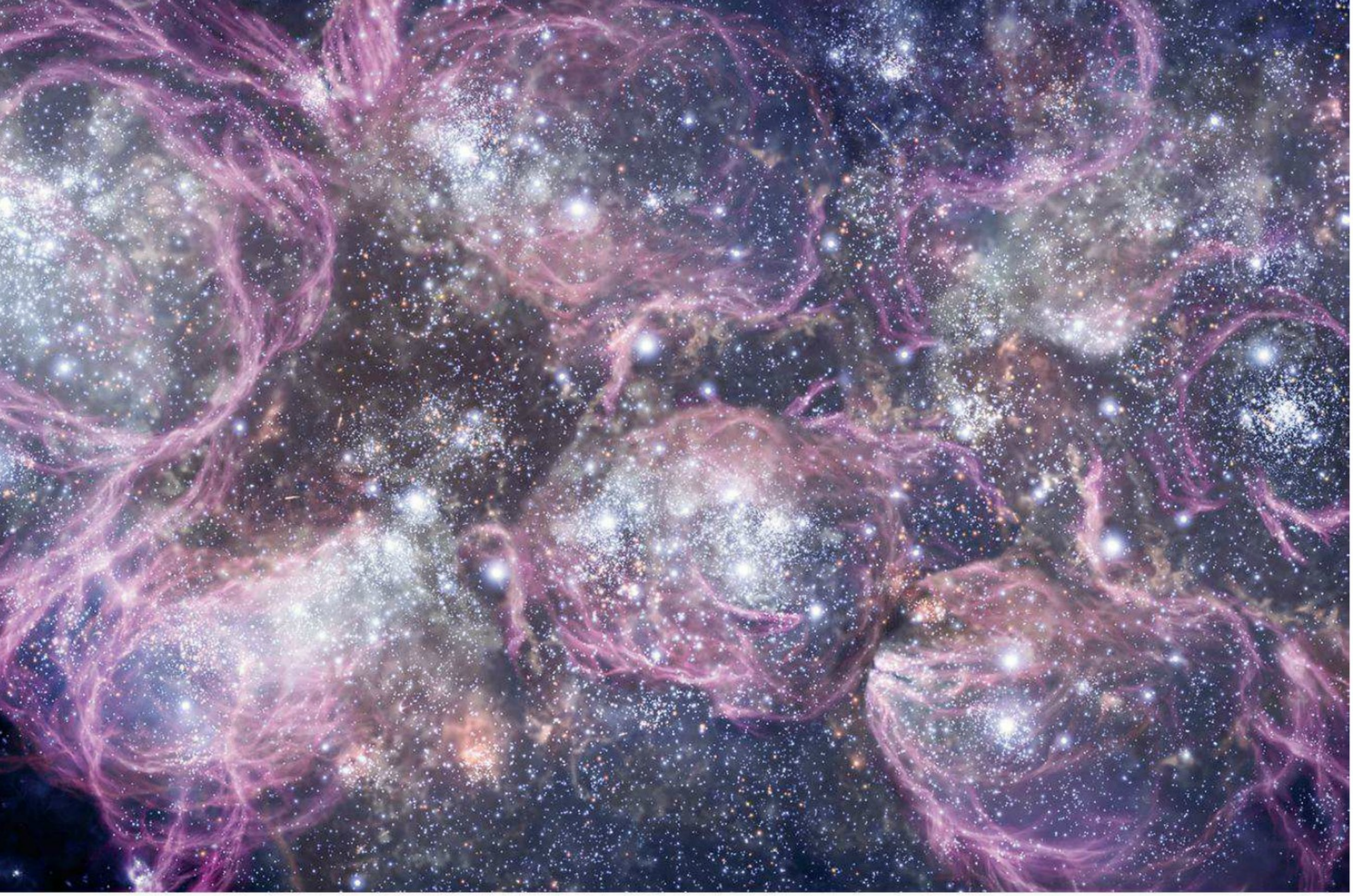
But the launch of the Wilkinson Microwave Anisotropy Probe (WMAP) changed all that. Still, astronomers' attempts during the previous century to narrow the age estimates makes for a fascinating detective story.

Before WMAP, the best approach for determining the universe's age used the much-debated Hubble constant, a figure that describes the rate at which the universe is expanding. To find the Hubble constant, astronomers observe distant galaxies and measure their distances (by using Cepheid variable stars or other objects of known intrinsic brightness) as well as how fast they recede from Earth. They then determine the Hubble constant by dividing the galaxy's speed of recession by its distance. Once they decide on a value for the Hubble constant, they can determine the age of the universe by calculating the constant's reciprocal.

But there was a problem. The values astronomers got for the Hubble constant depend on various assumptions about the universe's density and composition and the method used to determine distances. So, astronomers of different mindsets got different values for the constant.

They generally divided into two camps, one in the range of 50 kilometers/second/megaparsec, and the other up at 80 km/sec/Mpc. (A megaparsec equals 3.26 million light-years, or about 20 billion billion miles.) Therefore, the two groups estimated a range for the age of the universe of about 10 to 16 billion years. (The higher values of the Hubble constant produce younger age values for the universe.) Research by various groups, including Wendy Freedman and her colleagues in the Key Project — astronomers who were using the Hubble Space Telescope to measure the distances to many galaxies — narrowed in on a value toward the younger end of the scale. But uncertainties remained.

The other series of approaches to determine the universe's age attempted to measure directly the ages of the oldest objects in the universe. Astronomers can estimate the universe's age by measuring the decay of radioactive elements. This



STAR BLAST. **When the universe was less than a billion years old, it was little more than a sea of hydrogen and helium. A sudden blast of star formation turned on lights within the darkness.** NASA/ESA/ADOLF SCHALLER

precisely measures the ages of the oldest rocks on Earth at 3.8 billion years and the oldest meteorites at 4.6 billion years, dating the solar system.

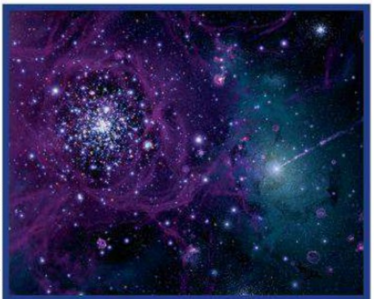
Applying this technique to gas in the Milky Way or to old stars is less precise, however, due to assumptions about the primordial abundances of various isotopes. The large windows for error in these calculations pointed to an age of the universe of 12 to 15 billion years, plus or minus 3 to 4 billion years.

Measuring the ages of ancient star clusters offered another avenue. By looking at the most luminous stars in a globular cluster, astronomers can fix an upper limit for the cluster's age. They look at the brightest stars on the so-called main sequence, the primary track on a plot of stars' brightnesses versus their temperatures.

Such studies of many globulars, based on refined distance measurements provided by the European Space Agency's Hipparcos satellite, suggested an age for many of the oldest stars of about 12 billion years. And astronomers think the age of globulars gives a pretty good indication for the age of the universe. That's because globulars contain hardly any heavy elements, and so had to be among the first objects to form.

Alternatively, astronomers measured the ages of white-dwarf stars, the shrunken remnants of stars that are as heavy as the Sun but only as large as Earth. By finding the faintest, and thus oldest, white dwarfs, astronomers estimated how long they have been cooling. Comprehensive attempts at cataloging white dwarfs and measuring their ages yielded about 10 billion years for the age of the Milky Way's disk. The galaxy's disk formed about 2 billion years after the Big Bang, yielding an age of the universe of about 12 billion years.

The discrepancies disappeared with the release of WMAP data in 2003. By carefully examining the microwave background radiation, astronomers were able to pin down the universe's age to 13.7 billion years, accurate to 1 percent. The result pretty much ended the debate, but what a debate it was. ■



NASA/ADOLF SCHALLER

BUILDING PROJECT. **When our galaxy formed, its spiral arms had not coalesced, and the sky was a sea of globular clusters.**

2 How **big** is the **universe?**

Two great debates have taken center stage in the search to answer this age-old question. In April 1920, Harlow Shapley and Heber Curtis argued over the scale of the universe in the great auditorium of the Smithsonian Institution's Natural History Museum in Washington.

In this discussion, which preceded Edwin Hubble's discovery of the nature of galaxies by just a few years, Curtis argued that the cosmos consists of many separate "island universes" — that the so-called spiral nebulae were distant systems of stars outside our Milky Way. Shapley argued that spiral nebulae were merely gas clouds in the Milky Way. He further placed the Sun much of the way out near the edge of the galaxy — the entire universe, in his view — whereas Curtis believed the Sun to be near the galaxy's center. Curtis was right about the large size of the universe but wrong about the Sun's place in the galaxy, whereas Shapley was wrong about the smaller universe and right about the Sun's location in it.

With the advent of many extragalactic distance measurements and two camps arguing for different results on the critical number called the Hubble constant, the expansion rate of the universe, astronomers staged a second great debate in 1996. The age and size of the universe are, of course, interrelated, and both depend critically on the Hubble constant.

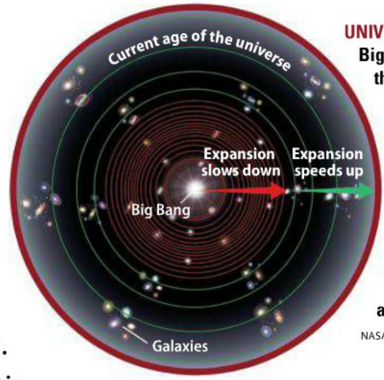
In the same auditorium used by Shapley and Curtis, galaxy researchers Sidney van den Bergh and Gustav Tammann argued over the question. Van den Bergh offered evidence supporting a high value of the constant (about 80 km/sec/Mpc), suggesting a young age and correspondingly small size of the universe. Tammann argued for a low value of the constant (about 55 km/sec/Mpc), which would indicate an older, larger universe.

As was the case with Shapley and Curtis, the antagonists van den Bergh and Tammann each provided crisp, clear-cut arguments and data supporting his side, and neither succeeded in convincing astronomers from the other camp. As yet, astronomers are limited by both assumptions and a lack of adequate data to agree on the cosmic distance scale.

Despite this, astronomers can set some limits on what must be true, based on the observations they have collected over the past century. Using the most powerful telescopes now online, astronomers see galaxies 10 or 12 billion light-years away. (A light-year equals about 6 trillion miles, or 10 trillion kilometers.) So the "horizon" of visibility is some 24 billion light-years in diameter.

But that's from our viewpoint. What about the horizons as seen from distant galaxies? It's possible the universe is much larger than the portions we can see. This will be the case in the likely event that the inflation hypothesis, put forth by MIT's Alan Guth, proves correct. This idea suggests the extremely young universe experienced a moment of hypergrowth so severe it ballooned from the size of a subatomic particle to a softball's size in an instant. If inflation occurred, then the universe is much larger than we might expect based on current observations.

Here's where it gets weird: If inflation happened, then it may have happened in many places (perhaps an infinite number) beyond the visible horizon and the limits of the space-time continuum we are familiar with. If this is so, then other universes might exist beyond our ability to detect them. Science begs off this question, as by definition science is about creating and experimenting with testable ideas. For now, it's wondrous to know we live in a universe that's at least 150 billion trillion miles across, and it may be much bigger than that. 50



UNIVERSAL SIZE. Since the Big Bang, the expansion of the universe has slowed and then sped up. In this illustration, concentric red circles show that galaxies migrated apart slowly during the first half of cosmic history, and then a mysterious force — dark energy — accelerated the expansion.

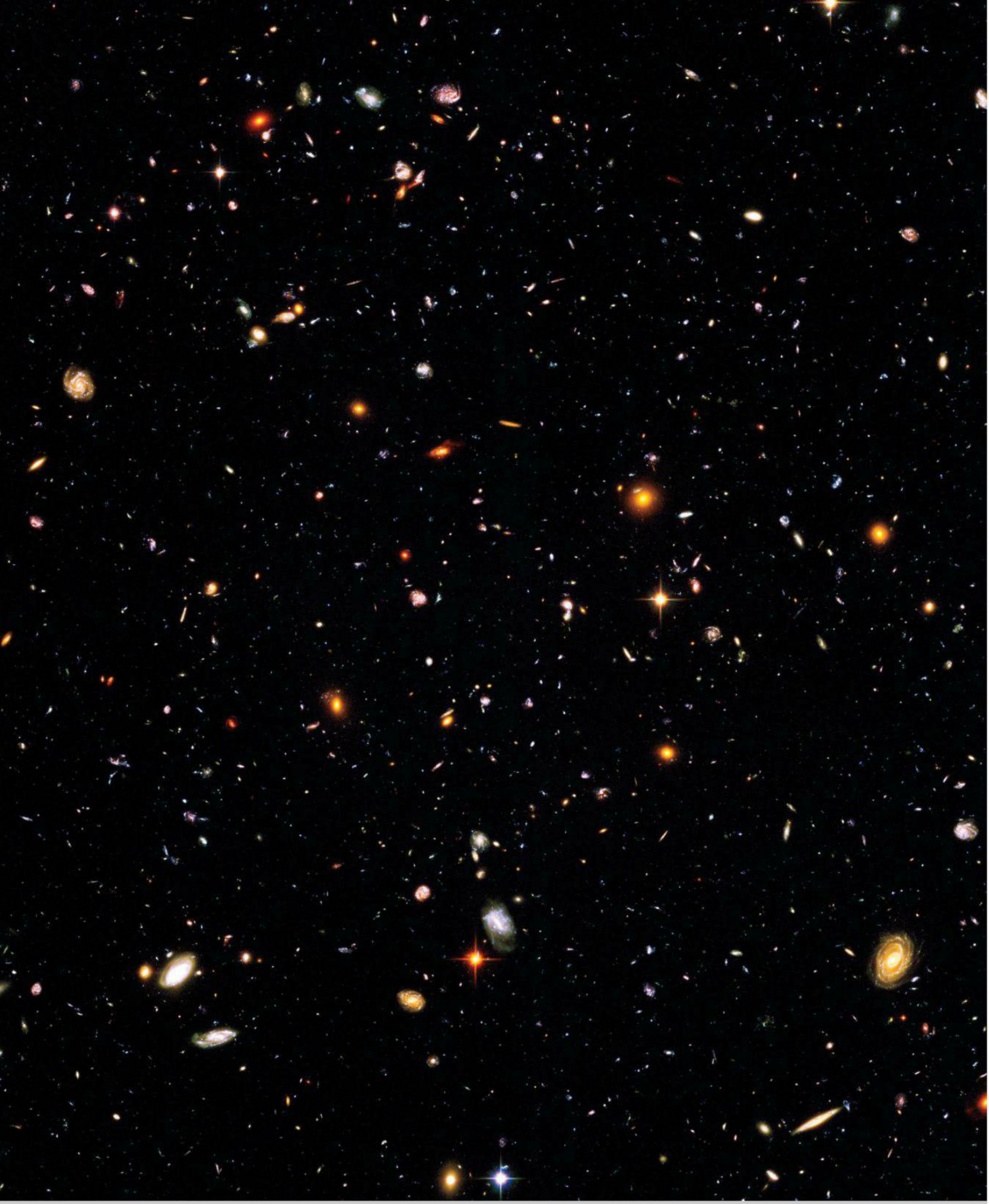
NASA/ANN FEILD (STScI)

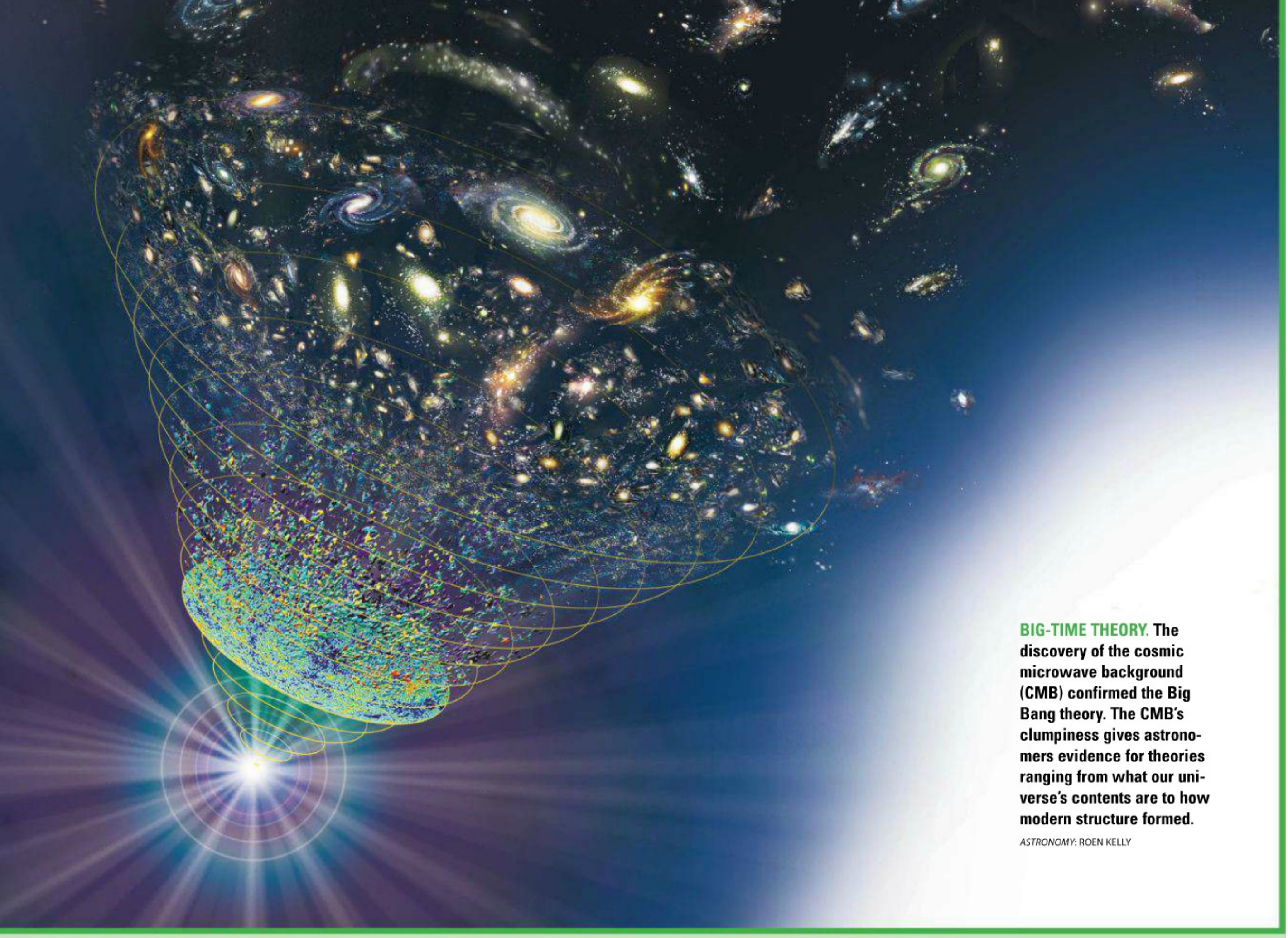
◀ **FAINT MYSTERIES.** Strange, young, star-forming galaxies (arrows) in this Hubble Space Telescope image from 2003 are less than a billion years old and represent a time when the universe was 7 times smaller than it is today.

NASA/H.-J. YAN, R. WINDHORST, AND S. COHEN (ARIZONA STATE UNIVERSITY)

▶ **ULTRA DEEP FIELD.** In 2005, when infrared and optical cameras on Hubble teamed up to weigh distant galaxies, astronomers found larger and more "mature" galaxies than they expected. In this deepest-ever portrait of the universe, we see back 12.7 billion years.

NASA/ESA/S. BECKWITH/THE HUDF TEAM





BIG-TIME THEORY. **The discovery of the cosmic microwave background (CMB) confirmed the Big Bang theory. The CMB's clumpiness gives astronomers evidence for theories ranging from what our universe's contents are to how modern structure formed.**

ASTRONOMY: ROEN KELLY

3

How **did** the **Big Bang** happen?

Virtually all astronomers and cosmologists agree the universe began with a "big bang" — a tremendously powerful creation of space-time that sent matter and energy reeling outward. The evidence is clear — from the underpinnings of Albert Einstein's general theory of relativity, to the detection of the cosmic microwave background radiation by Arno Penzias and Robert Wilson in the 1960s, to the confirmation of ripples in the fabric of ancient space-time from the Cosmic Background Explorer (COBE) satellite in 1992. But the devil is in the details, and that's where figuring out how Big Bang cosmology really works gets interesting.

The Big Bang model breaks down into several eras and key events. Standard cosmology, the set of ideas that is most reliable in helping to decipher the universe's history, applies from the present time back to about 1⁄100 second after the Big Bang. Before then, particle physics and quantum cosmology describe the universe.

When the Big Bang occurred, matter, energy, space, and time were all formed, and the universe was infinitely dense and incredibly hot. The often-asked question "What came before the Big Bang?" is outside the realm of science, because it can't be answered by scientific means. In fact, science says little about the way the universe behaved until some 10^{-43} second after the Big Bang, when the Grand Unification Epoch began (and which lasted only until 10^{-35} second). Matter and energy were interchangeable and in equilibrium during this period, and the weak and strong nuclear forces and electromagnetism were all equivalent.

The universe cooled rapidly as it blew outward, however, and by 10^{-35} second after the Big Bang, the epoch of inflation occurred, enlarging the universe by a factor of 10^{50} in only 10^{-33} second. During this wild period, cosmic strings, monopoles, and other exotic species likely came to be. As sensational as inflation sounds, it explains several observations that otherwise would be difficult to reconcile. After inflating, the universe slowed down its expansion rate but continued to grow, as it does still. It also cooled significantly, condensing out matter — neutrinos, electrons, quarks, and photons, followed by protons and neutrons. Antiparticles were produced in abundance, carrying opposite charge from their corresponding particles (positrons along with electrons, for example).

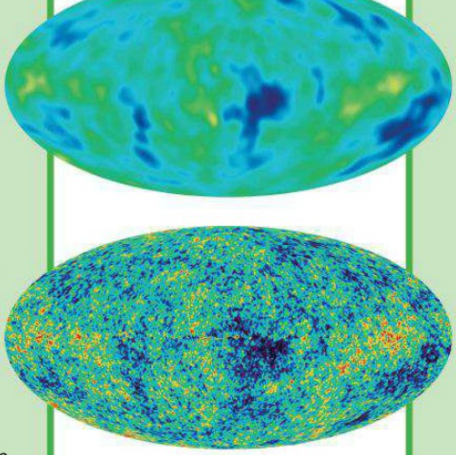
When the Big Bang occurred, matter, energy, space, and time were all formed.

As time went on and particles' rest-mass energy was greater than the thermal energy of the universe, many were annihilated with their partners, producing gamma rays in the process. As more time crept by, these annihilations left an excess of ordinary matter over antimatter.

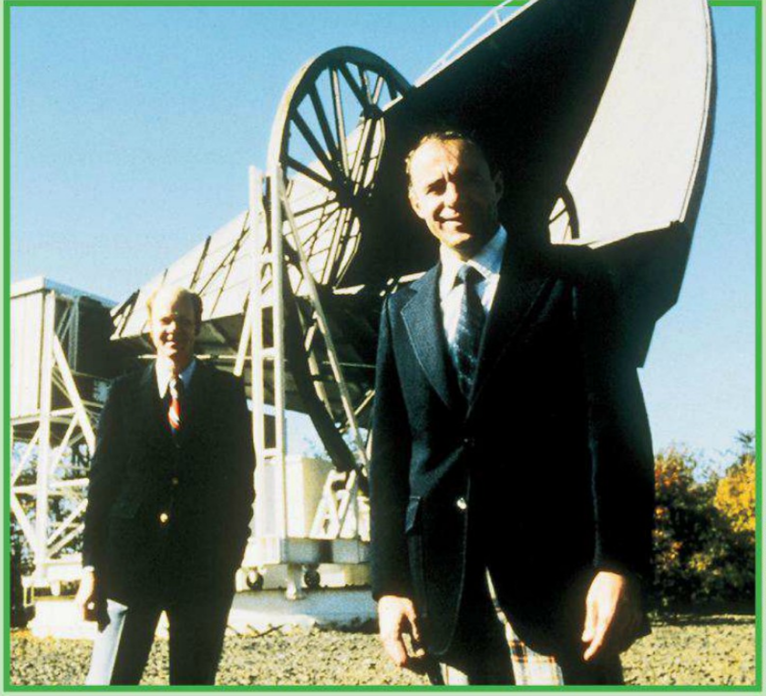
Chemistry has its roots deep in the history of the universe. At a key moment about 1 second after the Big Bang, nucleosynthesis took place and created deuterium along with the light elements helium and lithium. After some 10,000 years, the temperature of the universe cooled to the point where massive particles made up more of the energy density than light and other radiation, which had dominated until then. This turned on gravity as a key player, and the little irregularities in the density of matter were magnified into structures as the universe expanded.

The relic radiation of the Big Bang decoupled nearly 400,000 years later, creating the resonant echo of radiation observed by Penzias and Wilson with their radio telescope. This decoupling moment witnessed the universe changing from opaque to transparent. Matter and radiation were finally separate.

Observational astronomers consider much of the history of the early universe the province of particle physicists and describe all of what happened up to the formation of galaxies, stars, and black holes to be "a lot of messy physics." They are more interested in how the first astronomical objects, the large-scale inhabitants of the universe, came to be about 1 billion years after the Big Bang. But before observational astronomers can gain a clear picture of that process, they need to consider the role of the wild card — dark matter.



HIGH-RES ECHO. Evidence for the Big Bang comes from detailed data from the Cosmic Background Explorer (COBE) and Wilkinson Microwave Anisotropy Probe (WMAP) satellites. In 1992, COBE produced the first good CMB map (top); nine years later, WMAP followed with a far-more detailed version. NASA/WMAP SCIENCE TEAM



ASTRONOMICAL SOCIETY OF THE PACIFIC

COSMIC DISCOVERY. Robert Wilson (left) and Arno Penzias unexpectedly discovered the cosmic microwave background radiation with this horn-shaped antenna.

DARK-MATTER MAP. Gravitational lensing within galaxy cluster CL0025+1654, mapped by the Hubble Space Telescope, revealed an enormous halo of dark matter (in blue) must surround the brighter galaxies.

J.-P. KNEIB/ESA/NASA

4

What is dark matter?

Astronomers might be more confident about their picture of the universe were it not for dark matter. Observations show that the universe is populated with some unseen form of matter — and plenty of it. Astronomers attempt to "weigh" the universe in a variety of ways. They observe the effects of dark matter on astronomical objects that vary from small to large.

Dark matter was posited by Dutch astronomer Jan Oort in the 1930s when he studied star motions in the Sun's neighborhood. Because the galaxy was not flying apart, he reasoned, enough matter must reside in the disk to keep the stars from moving away from the galaxy's center. Oort postulated that, in the Sun's neighborhood, 3 times as much dark matter existed as bright matter.

Stronger evidence came later as astronomers examined the luminous disks and halos of galaxies. By studying the rotation curves of galaxies, astronomers can glimpse how some dark matter is distributed.

The process works like this: Newton's law of gravity says stars revolving about the center of a galaxy should slow dramatically the farther away they are from the galactic center. But the rotation curves of galaxies are "flat," meaning the stars in an individual galaxy orbit at a steady velocity independent of how far from the galaxy's center they are. The most logical explanation for this is that massive spherical halos of dark matter surround the visible matter in galaxies.

Other clues for dark matter come from studying galaxy clusters. Also in the 1930s, American astronomer Fritz Zwicky deduced much larger clouds of dark matter exist in the Coma cluster of galaxies, about 300 million light-years from Earth. By looking at the Doppler shifts of individual galaxies in the cluster, Zwicky found 10 times the mass of the visible light in the cluster must have been present to keep the galaxies gravitationally bound.

So what is dark matter? One of the great mysteries of recent decades centers on exactly what makes up this stuff. Possibilities abound, and each has its strengths and weaknesses in terms of explaining astronomers' observations. They include massive numbers of normal neutrinos; MACHOs (massive compact halo objects) such as brown dwarfs, neutron stars, and black holes; and WIMPs (weakly interacting massive particles) such as exotic particles, axions, massive neutrinos, and photinos.

Whatever it consists of, dark matter carries enormous implications for the structure and future of the universe. At least 90 percent of cosmic matter consists of baryonic and non-baryonic dark matter. (Baryons are particles consisting of three quarks that interact through the strong nuclear force — including protons and neutrons.)

Of non-baryonic dark matter, two basic types exist: hot dark matter (HDM) and cold dark matter (CDM). The "temperature" in each model refers to the particles' velocities. Neutrinos represent the likeliest HDM candidate, while CDM possibilities include WIMPs. Baryonic dark matter, which constitutes a small percentage of the total, includes the MACHOs.

An HDM-dominated universe would suggest little matter exists between clusters of galaxies. Recent observations show this is not the case, however, largely discrediting the HDM model of the universe.

Had massive numbers of neutrinos been created in the early universe, they likely would have smoothed out the ripples in the "soup." This didn't happen. The vast majority of dark matter, therefore, must exist in some form of CDM. The odds are leaning toward massive, exotic, relatively slow-moving particles. But astronomers must make great strides before we'll know the exact identity of dark matter, one of the century's greatest astronomical mysteries.

COSMIC TRAIN WRECK. NGC 4650A, a "polar ring galaxy," represents a spectacular collision of galaxies. The galaxy extends so far out that it affords astronomers the chance to study dark matter in an odd, valuable, natural laboratory.

NASA/THE HUBBLE HERITAGE TEAM

5 How **did** galaxies **form**?

While observational tests on the details of cosmology proceed apace, astronomers are focusing on the mechanics of how matter came together in the early universe. The key question is: Did galaxies, stars, or black holes come first?

The infant universe was a relatively uniform sea of several-thousand-degree gas and dark matter — the unseen, mysterious, and much more predominant form of matter that is indirectly known to exist because of its huge gravitational influence on galaxies. But how galaxies, stars, and black holes came together is the key to understanding the puzzle of the early universe.

Based on the microwave background data, astronomers think matter coalesced when the universe cooled and became "transparent" 380,000 years after the Big Bang. Structures like stars and galaxies formed about 1 billion years after the Big Bang. But exactly how matter clumped is open to future research.

Deciphering galaxy formation goes back to Walter Baade, who studied stars in galaxies and tried to interpret how the galaxies formed. One of the premier researchers at California's Mt. Wilson Observatory in the 1950s, Baade discovered a group of stars around the Milky Way with few metals (elements heavier than hydrogen and helium). These stars are ancient, probably 11 billion years old. Metals thrown out into interstellar space by supernovae and other processes were eventually incorporated into younger stars in our galaxy.

Baade's discovery led to a model of galaxy formation in the 1960s nicknamed ELS, after Olin Eggen, Donald Lynden-Bell, and Allan Sandage. The ELS model says galaxies collapsed as single objects out of gas clouds. As the gas fell in by gravity, it first formed a spherical halo. As more gas coalesced, it began spinning and was enriched with metals, creating disks inside galaxies.

NASA/THE HUBBLE HERITAGE TEAM

WHEEL IN THE SKY. Hoag's Object is a ring of hot, blue stars wheeling around a cooler, yellow nucleus. The whole galaxy measures about 120,000 light-years across, slightly larger than the Milky Way.

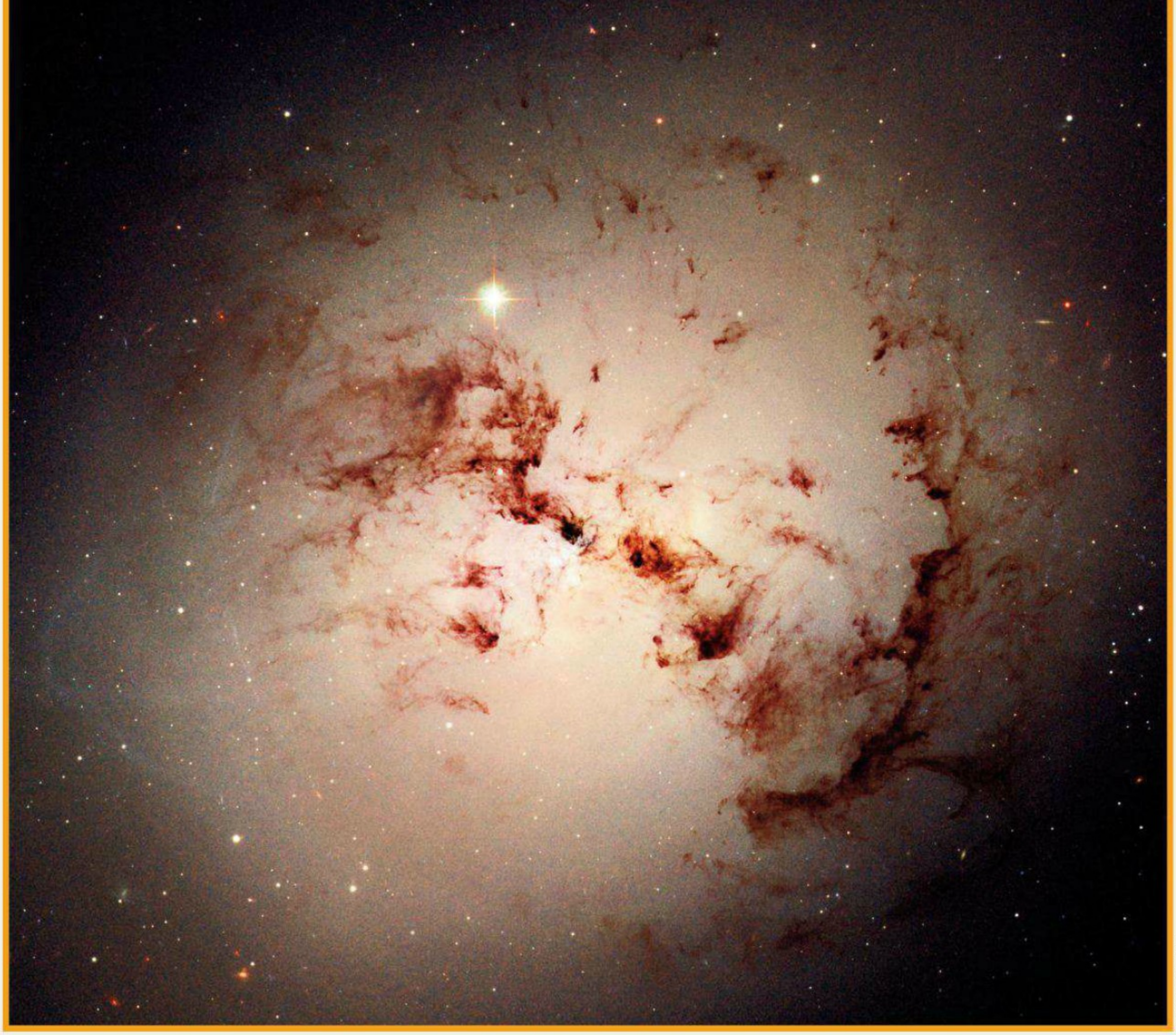
A different idea proposed recently is the merger theory. It could have been hatched on Wall Street when the merger buzz was about AOL with Time-Warner and Exxon with Mobil. But those mergers are minuscule compared with the unions of protogalaxies — blobs of gas without stars that gravitated together and merged to form galaxies in the early universe — and galaxies of various sizes merging later with other galaxies.

Indeed, over the past few years it has become increasingly clear that many galaxies, perhaps the vast majority, formed when small gas clouds came together, merging into larger and larger structures as time went on. This is called the bottom-up path.

"We don't really know which is the dominant path yet," says John S.

NASA/THE HUBBLE HERITAGE TEAM

A STAR-LADEN SOMBRERO. Beautifully formed spiral galaxies like the Sombrero Galaxy, seen from our line of sight as edge-on, coalesced as clumps of matter aggregated in the early universe.



P. GOUDFROOIJ/STScI

LOOPS AND BLOBS. **The disturbed galaxy NGC 1316 hints at its chaotic past. Probably the result of a head-on collision between two galaxies, NGC 1316 exhibits great turbulence in its core.**

Gallagher III of the University of Wisconsin. "There's a strong theoretical prejudice to make small things and have them grow bigger, by having gas fall into them or capturing their neighbors. But astronomers haven't yet proven that this is the main way it happens." However, circumstantial evidence is accumulating that mergers are the primary form of making galaxies.

Two "deep fields" imaged by Hubble show distant galaxies and reveal numerous blob-like objects that appear to be protogalaxies. These are likely the fragments that clung together to form the larger "normal" galaxies we see around us. Some galaxy experts believe the Milky Way may have formed from the mergers of 100 or more small galaxies over time.

The question of whether galaxies came together as gas, then commenced forming stars, or whether stars formed from little pockets of gas and then aggregated into galaxies, is unclear. A third possibility is that black holes formed initially as dense pockets of matter. They then swept up material around themselves, and galaxies formed from the surrounding gas that didn't get sucked in by the black holes.

> Black holes exist in the centers of most large and medium-sized galaxies.

Just 3 decades ago, astronomers thought black holes, regions of intense gravity from which no matter or light can escape, were mathematical oddities. But now, astronomers armed with large telescopes infer their presence in the centers of most large and medium-sized galaxies. They are the driving engines in distant quasars, highly energetic infant galaxies. Astronomers are now leaning toward a consensus that black holes inhabit the cores of most galaxies, but perhaps not the small ones.

6

How common are black holes?

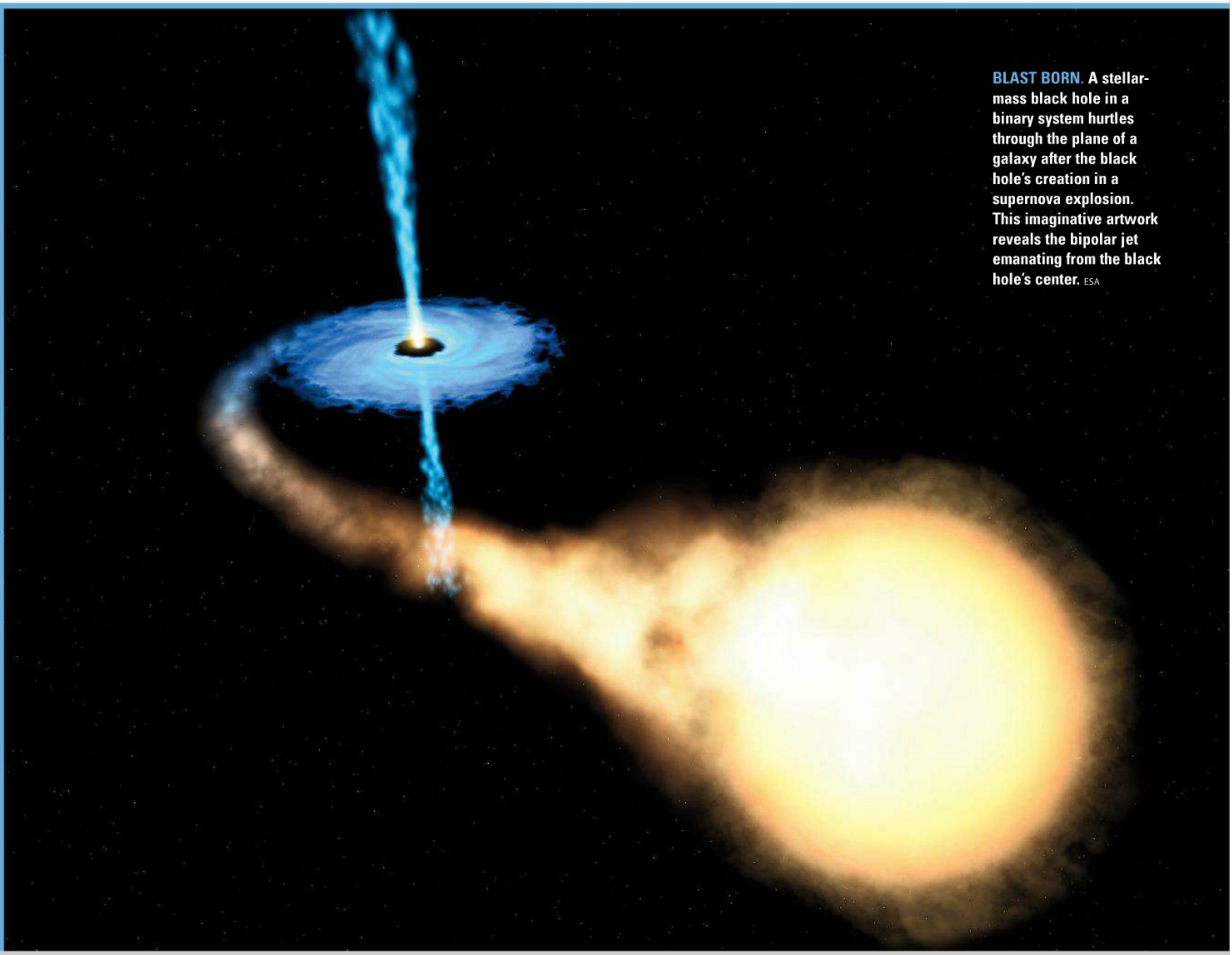
On the heels of Einstein's general theory of relativity, German theoretical astrophysicist Karl Schwarzschild provided a detailed proposal on the existence of black holes in 1916.

The concept of black holes goes all the way back to the 1780s, when John Michell and Pierre Simon Laplace envisioned "dark stars" whose gravity was so strong that not even light could escape. As with many startling ideas, the acceptance of black holes as real objects took a long time.

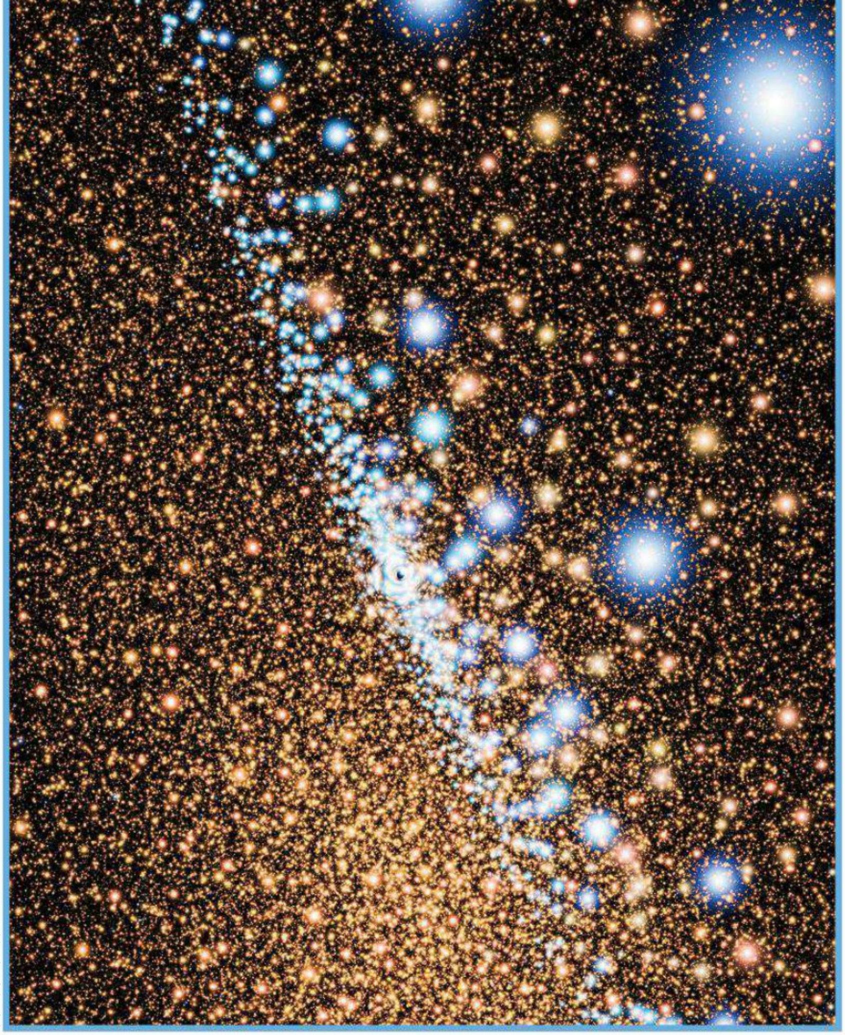
It wasn't until astronomers were able to observe lots of galaxies and massive binary star systems in the 1970s and early 1980s that it became obvious black holes must exist. In the 1990s, it became clear to astronomers that black holes not only exist, but are plentiful.

A black hole is a region of space-time affected by such a dense gravitational field that nothing, not even light, can escape it. Consider the escape velocity on Earth: If you could throw a baseball at a velocity of 7 miles per second, you could hurl it into space, overcoming Earth's gravitational tug. As massive objects are crushed into smaller volumes, their gravitational tug increases dramatically. In a black hole, the escape velocity exceeds 186,000 miles per second — the speed of light — and everything inside the hole is trapped.

So, if black holes are black, how do astronomers know they exist? Not directly visible, black holes must be detected by their effects on nearby stars, gas, or dust. In the Milky Way, many stellar black holes — with masses in the range of about 10 times



BLAST BORN. A stellar-mass black hole in a binary system hurtles through the plane of a galaxy after the black hole's creation in a supernova explosion. This imaginative artwork reveals the bipolar jet emanating from the black hole's center. ESA



ESA/NASA/ADOLF SCHALLER

BLACK-HOLE NEIGHBOR. **A disk of young, blue stars encircles a supermassive black hole at the center of the Andromeda Galaxy (M31) in this artwork. The region of the black hole lies at the center of the disk, barely visible.**

that of the Sun — exist in binary star systems.

When a massive star dies, it explodes as a supernova. But the core of the exploded star remains behind as either a neutron star or, if it's heavy enough, a black hole. Black holes become visible when they exist in X-ray binaries, twin star systems in which one of the stars has become a black hole and the other is still there. The black hole shreds or perturbs its companion, the result of which unleashes X-ray energy.

But star-sized black holes aren't the only type. Research with the Hubble Space Telescope and large ground-based instruments has uncovered several dozen clear-cut cases of supermassive black holes in the centers of galaxies. These are monstrously powerful black holes that contain anywhere from a million to a billion solar-masses of material. In fact, the Milky Way holds a relatively modest million-solar-mass black hole. Many hundreds of galaxies are what astronomers call "active," producing high-energy emission from their cores, and are also suspected of harboring black holes.

As observations of distant galaxies accumulate, it has become clear extragalactic black holes are common in the universe. It may be that black holes formed within all medium- and large-sized galaxies (probably not in the dwarf galaxies, where there's not sufficient mass) early in the universe.

It's possible that "seed" black holes even predated the formation of galaxies and stars, which formed around these gravitational wells. In any event, the "active" phases of some galaxies occur when fresh material falls into the central black holes, feeding them and emitting vast amounts of radiation we see with telescopes. Such an idea is akin to a "healthy" galaxy going through a periodic bout of "flu," which upsets and reconfigures its system.

The idea that black holes are common got a boost in 2001, when the Chandra X-ray Observatory completed a survey of the X-ray sky and found an abundance of supermassive black holes in two "deep fields." The Chandra data showed that these giant black holes were more active in the past than they are today, fitting the evolutionary picture nicely. The Chandra scientists provided a glimpse of galaxies like the young Milky Way and found them active. Our galaxy was probably active as well before its central black hole consumed most of the material around it and settled down into a quieter life.

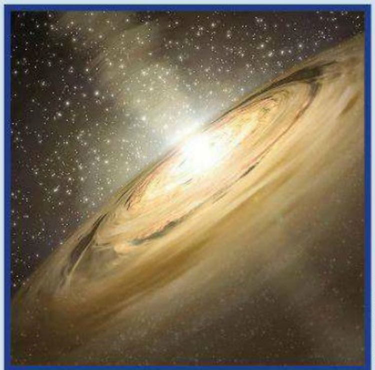
In addition to ordinary black holes, theoreticians have proposed "wormholes," black holes with different degrees of rotation and electric charge. Movies suggest a wormhole could lead to travel through the space-time continuum. But no evidence exists as yet for wormholes, and, besides, the ride would be a little rough. Encountering a black hole of any type, your body (and spacecraft, etc.) would be pulled into a very long line of protons — before getting fried by X rays and gamma rays — which would make getting anywhere you went a most unpleasant journey.

NASA/THE HUBBLE HERITAGE TEAM

COSMIC SEARCHLIGHT. A supermassive black hole at the center of the galaxy M87 in Virgo fires a jet of material outward.

7 How many **planets** are in the **solar system**?

You might think astronomers know the solar system, the region of space immediately closest to home, pretty well. And they do. But they might not know its whole story.



NASA/JPL-CALTECH

PLANET MAKER. In this artwork showing the early solar system, an enormous dust disk stretches around the Sun and serves as a breeding ground for new planets as material clumps together.

In fact, it's possible another planet lurks beyond Neptune, or even a faint, distant companion star to the Sun. Hypothetical planets in the solar system — along with real ones — have turned up in some pretty strange places.

Of course, the bright naked-eye planets — Mercury, Venus, Mars, Jupiter, and Saturn — were all known in antiquity and revered as gods because they showed free will to move among the stars. The first telescopically discovered planet was Uranus, found by William Herschel in 1781. After orbital calculations suggested a massive tug on Uranus being applied farther out, Johann Galle and Heinrich D'Arrest discovered Neptune in 1846.

Perturbations in Neptune's orbit suggested yet another, more distant planet, and many searches were conducted as early as 1877; Pluto was finally found by Clyde Tombaugh in 1930 by comparing pairs of photographic plates and detecting its motion. Oddly enough, the perturbations weren't really there, or at least Pluto wasn't massive enough to cause them. In 2006, astronomers decided Pluto wasn't up to planetary standards, and so demoted it to a "dwarf planet."

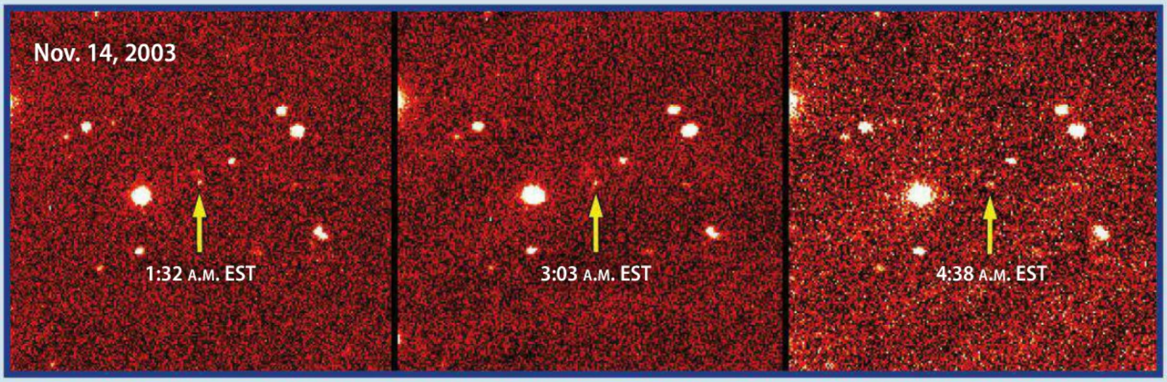
Does the number 8 really constitute the whole inventory of the Sun's planets? Many mathematical and observational exercises have led astronomers to suspect other major bodies orbit the Sun. As early as 1841, astronomers commenced a search for various "Planet Xs." The first one turned out to be Neptune. The second was Pluto, after some seven different trans-Neptunian planets (with different masses and orbits) had been proposed by the most active searcher, E. C. Pickering, alone.

But even after Pluto's discovery, astronomers predicted planets beyond, mostly on theoretical grounds. In 1946, Francis Sevin predicted the existence of "Transpluto," a planet 7 billion miles (11 billion kilometers) from the Sun (Pluto's average orbital distance is 3.6 billion miles).

In the 1950s, others hypothesized similar distant planets. Twenty years later, Tom van Flandern of the U.S. Naval Observatory became convinced another planet existed based on the orbital motions of Uranus and Neptune. He and a colleague searched for such a planet, but it was never found.

In 1987, John Anderson of JPL carefully examined the trajectory of the Pioneer 10 and 11 spacecraft and concluded a more-distant planet may exist, with a mass of about 5 Earths and an orbital period of 1,000 years. Conley Powell, also of JPL, investigated the orbital data of Uranus and hypothesized a planet of 3 Earth-masses some 5.6 billion miles (9.0 billion km) from the Sun. When a search took place at Arizona's Lowell Observatory using the parameters

DISTANT WANDERER. Discovered in 2003, Kuiper Belt object Sedna glows faintly. Its discovery intensified debate over the definition of "planets."



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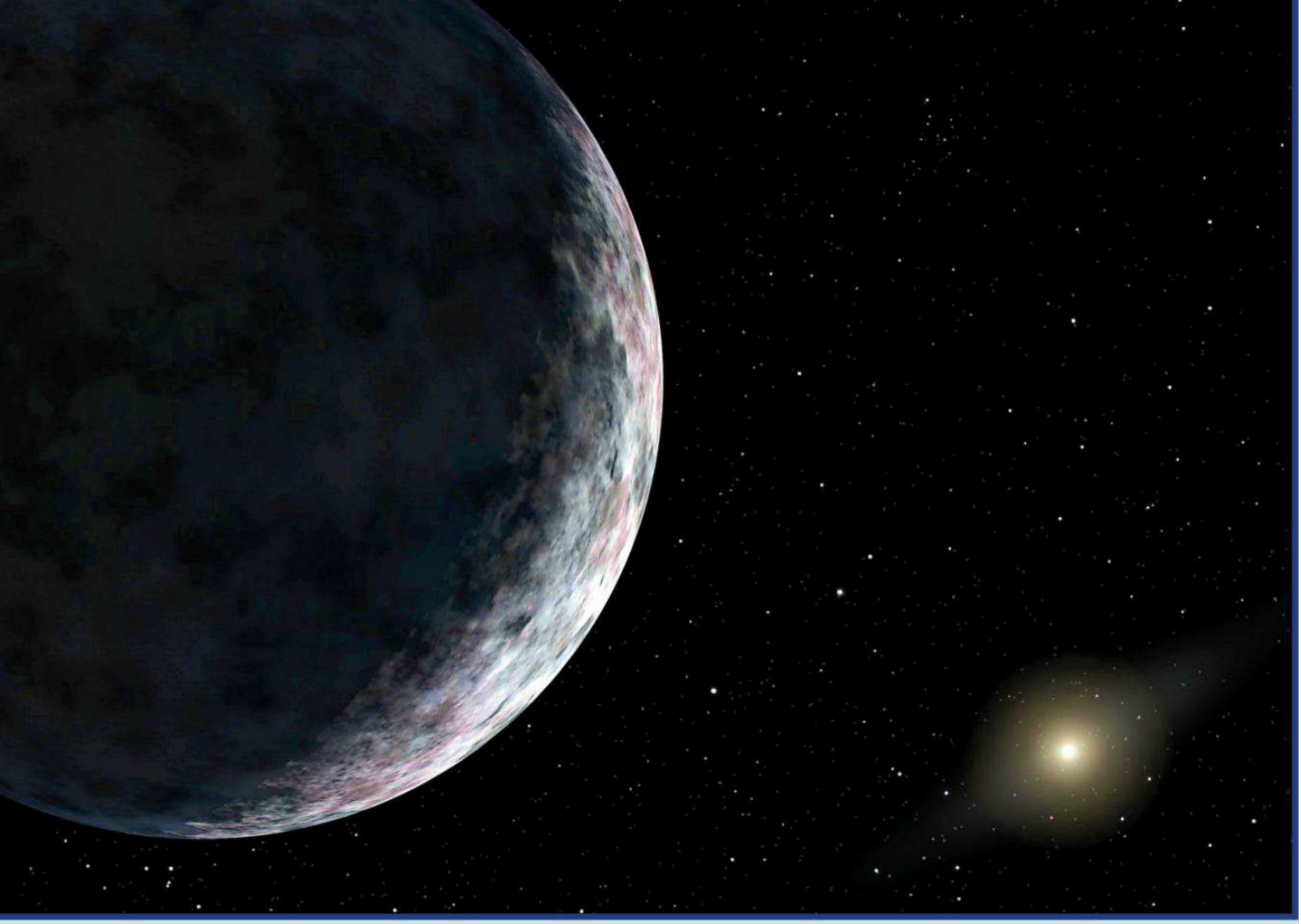


PLANET 10? In 2005, astronomers discovered Eris (seen here in an artist's rendition), which was announced as "the tenth planet" before Pluto's demotion. Lying 10 billion miles from the Sun, it is the most distant large body known in the solar system. NASA/JPL-CALTECH

from Powell's calculations, nothing of the correct brightness in the right spot turned up. Although a Planet X may exist, none has been found.

Still, intense interest in the outer solar system has paid off handsomely. With the first discovery of a so-called Kuiper Belt object in 1992, David Jewitt, Jane Luu, and other astronomers have uncovered a new element of the solar system. As many as 70,000 small bodies — asteroids and burned-out comets — exist in a zone extending from the orbit of Neptune outward, some 2.8 billion to 4.5 billion miles (4.5 to 7.2 billion km) from the Sun.

The Kuiper Belt discoveries have infused new sophistication into planetary scientists' understanding of solar system dynamics. It's what led to Pluto's demotion. And it leads to the most important question: What makes a planet, anyway? In 2006, the International Astronomical Union decided (for now, at least) that a planet is any object orbiting a star that is neither a star itself nor another planet's moon; contains enough mass for its gravity to have forced it to take on a spherical shape; and is big enough to have cleared its orbit.

The most important question has to be: What makes a planet, anyway?

Other hypotheses about solar system monsters have come and gone. There was Vulcan, an intra-Mercurial planet, thought to exist in the late-19th century (and briefly revived based on flawed observations in 1970–1971). There were phantom moons reported around Mercury, Earth, Venus, and Mars, off and on. There was "Nemesis," a proposed distant companion star to the Sun, that lurks about 1 light-year away and occasionally kicks a new set of comets sunward from the Oort Cloud.

The latest alarm came in 1999, when researchers in the United Kingdom and at Louisiana State University proposed the existence of a planet inside the distant Oort Cloud. But none of these ideas have panned out or been verified by observation. At the least, we have a middleweight star with 8 planets, 4 dwarf planets, and a vast collection of small bodies orbiting it. But make no mistake: Astronomers will keep watching.

8

Are we **alone?**

Astronomers as yet lack the technology to detect life on planets light-years away. But the first step of looking for chemical signatures in the spectra of stars with planets will lead to educated guesses about the habitability of certain extrasolar planets. Orbiting space telescopes just a few years away from possible launches include three powerful instruments that will heighten the ability to detect earthlike planets and perhaps the signatures of living beings: the Terrestrial Planet Finder, the James Webb Space Telescope, and Darwin.

The whole issue about life on other worlds begs the question, "What is life and how would we recognize it?" Certainly, living things are made of cells (or a cell) and share three critical processes that make them alive. They ingest energy, excrete waste energy, and pass on their genes by reproducing themselves. They respond to their environments. They maintain homeostasis, or internal balance. They also evolve and adapt. Some have evolved to the point where they can walk and think about the universe that surrounds them. We are literally products of the universe. Most of the atoms and molecules in our bodies were created in the engines of stars, and the energy we receive, that enables life, comes from our star, the Sun.

But life on other planets may be very different. We can imagine a glimpse of what it might be like even by looking at bizarre and different environments on Earth. For one thing, the vast majority of life on Earth comes in the form of primitive bacteria, fungi, molds, and other squishy, incredibly tiny organisms. (Viruses are not considered alive because they require a host on which to perform the functions of "life" — which for them amounts to cannibalizing cells.)

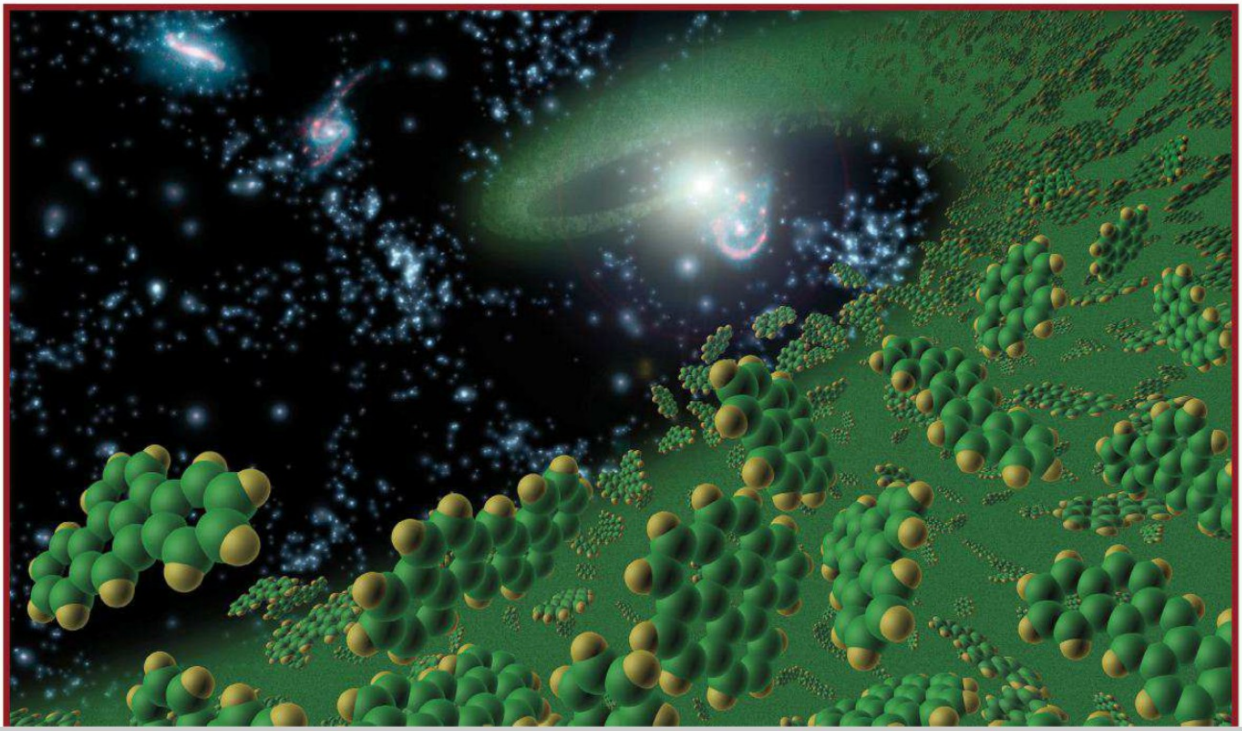
Life as complex as trees, rats, or insects may be so incredibly rare compared with such nearly invisible living beings, we could explore 1,000 living planets and never see anything but microbes. But consider the numbers: 200 billion stars in the Milky Way and at least 125 billion galaxies in the universe. The numerical possibilities for extraterrestrial life are astonishing, even if only a tiny fraction of planets with life have evolved any kind of sophisticated critters.

NASA

LONELY UNIVERSE. In this portrait of Earth and the Moon snapped by Voyager 1 in 1977, the vastness of deep space receives only a hint.

"We have one planet, one example, one history, and we have intelligence," Carl Sagan was fond of saying. "Intelligent species should be spread liberally throughout the universe." Certainly the majority of Americans believes in the existence of extraterrestrial life. Indeed, probably a slim majority believes UFOs

IT'S A LIVIN' THING. Complex hydrocarbons represent the building blocks of life in this illustration. NASA's Spitzer Space Telescope has detected hydrocarbon chains 10 billion years back in time, suggesting life may have started early in the universe.



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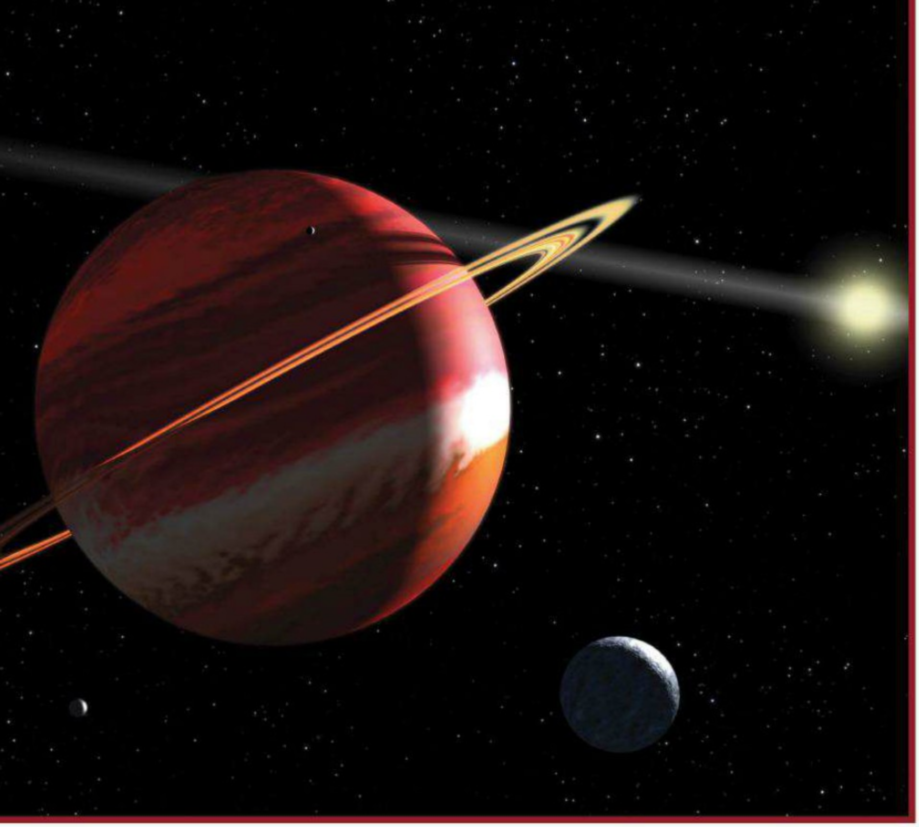


EXOPLANET ZOO. **Astronomers have found more than 200 planets beyond our solar system. The nearest one known lies 10.5 light-years away and orbits the star Epsilon Eridani. In this illustration, a hypothetical family of moons orbits this planet.** NASA/ESA/G. BACON (STScI)

have carried intelligent beings to our solar system, and possibly to Earth's surface. But the extraterrestrial-life debate is not a democratic one, not something to be subjected to a popular vote.

Distinguished scientists such as Harvard anthropologist Irven DeVore have made detailed cases suggesting the evolution of intelligent life on Earth itself was unlikely, that it may have resulted from a whole series of unlikely coincidences of evolution. For example, DeVore asserts, "Evolution is history; it's not a series of predictions. Natural selection, which is the engine driving evolution, is an uncaring, blind process. From the fossil record, we can judge that 99.9 percent of all species that ever lived have gone extinct. There have lived as many as 50 billion species. Of those, only one made civilizations."

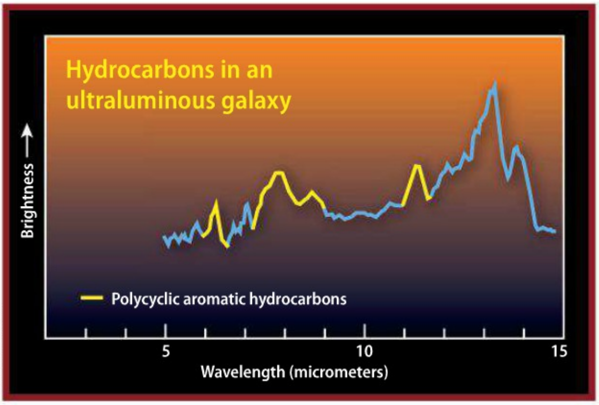
But Seth Shostak of the SETI Institute in Mountain View, California, sees a different picture. In the 1920s and 1930s we thought planetary systems were rare, he reminds us. Now, we see planetary systems around hundreds of nearby stars, and the count rises with each search.

Until the 1970s, scientists believed cooking up DNA on a planetary surface was probably very special. "But now we know that not only is physics universal, but probably biology, too," says Shostak.

On Earth, the first single-celled organisms arose soon after the period of heavy bombardment by comets and asteroids slackened, some 3.8 billion years ago.

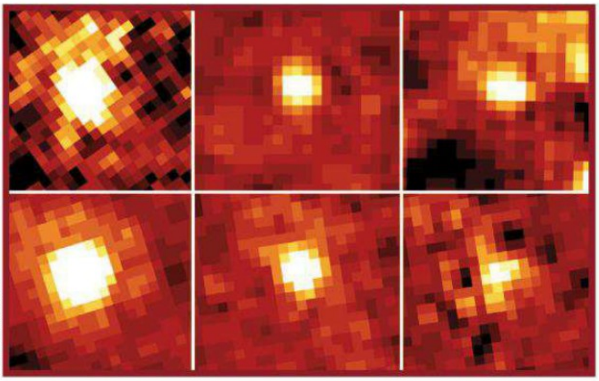
This suggests life might get started elsewhere easily, too.

"Of course, the so-called Fermi paradox argues against this spreading out," Shostak reminds us, "by simply asking, 'So where is everybody?'" But if you woke up in the middle of Nevada, you might wander about and conclude you're the only person on the continent. Absence of evidence is not evidence of absence.



NASA/JPL-CALTECH

IS ANYONE OUT THERE? **A spectrum made with the Spitzer Space Telescope in 2004 shows the signature of polycyclic aromatic hydrocarbons, the fingerprint of the building blocks of life. Seeing these compounds in a distant galaxy, 10 billion light-years away, suggests the possibility of abundant life in the cosmos.**

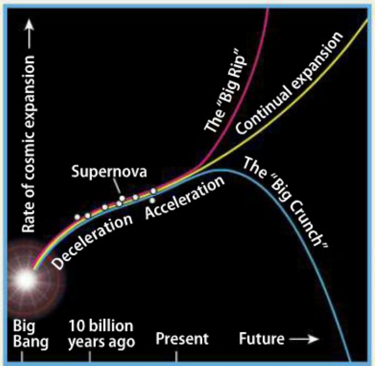


NASA/JPL-CALTECH

OTHER SUNS. **The Spitzer Space Telescope imaged six stars with known planets. The Sun-like stars are encircled by disks of debris that have been detected by their infrared glows.**

9

What is the **fate** of the **universe**?



ASTRONOMY: ROEN KELLY

BIG-BANG TESTS. Careful observations of supernovae throughout the universe will allow astronomers to determine the end-game answer. The likeliest scenario, in agreement with Einstein, is the indefinite-expansion model.

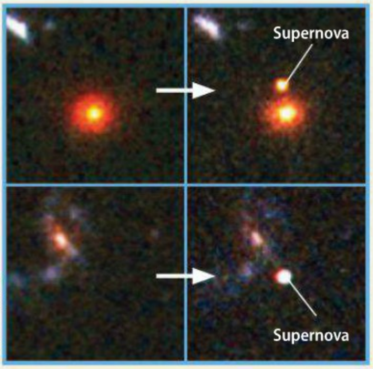
The answer to this ancient question is still unknown, but there are strong observational leanings toward a clear outcome. And, that, in and of itself, would have surprised most astronomers who thought about the subject during the past 70 years.

For most of recorded history, the answer would have been simple: The universe has always existed and always will. Few people challenged the dogma or even suspected it might not be true.

That started to change in the 1910s, with the publication of Albert Einstein's general theory of relativity. The first models developed from Einstein's equations showed the universe does not have to be static and unchanging, but it can evolve.

In the 1920s, Belgian priest and astronomer Georges Lemaître developed the concept of the Big Bang. Coupled with Edwin Hubble's observations of an expanding universe, astronomers were coming around to the idea that the universe had a beginning — and could have an end.

It wasn't until the 1960s that strong observational evidence supported the Big Bang. The two breakthroughs were the discovery of the cosmic microwave background radiation by Penzias and Wilson, and the realization that active galaxies existed preferentially in the distant universe, which meant they existed when the cosmos was much younger than it is today, and so the universe has been evolving.



NASA/A. RIESS (STScI)

DISTANT SUPERNOVAE. Dark matter rules the cosmos. Each left panel shows a host galaxy, while the matching right panel reveals a fainter-than-expected supernova in that galaxy.

By the 1980s, most astronomers were convinced the universe began with a bang, but they had little clue how it would end. There were basically three scenarios, all based on how much matter the universe contained. If the cosmos had less than a certain critical density, the universe was "open" and would expand forever; if the density were above the critical value, the expansion was "closed" and would ultimately stop and then reverse, leading to a "Big Crunch"; if the universe were at the critical density, it was "flat," and expansion would continue forever, but the rate would eventually slow to zero.

Observations seemed to favor an open universe, with only about 1 percent of the matter needed to halt expansion. But astronomers knew a lot of dark matter — non-luminous material that nevertheless has gravitational pull — existed. Would it be enough to stop the expansion? No one knew.

Matters got more interesting in the 1980s, when Alan Guth proposed his inflation hypothesis. This says a brief period of hyperexpansion in the universe's first second made the universe flat. Astronomers eagerly accepted inflation because it solved some of the problems with the Big Bang model, and also was philosophically pleasing.

But the most remarkable development came in the late 1990s. Astronomers using the Hubble Space Telescope and several large ground-based instruments were examining dozens of distant type Ia supernovae. This variety of exploding star arises when a white dwarf in a binary system pulls enough matter from its companion star to push it above 1.4 solar-masses. At that stage, the white dwarf can no longer support itself, so it collapses and explodes.

Because all these exploding white dwarfs have the same mass, they all have the same approximate peak luminosity. Simply measure how bright the type Ia supernova appears, and you can calculate its distance.

That's exactly what the Supernova Cosmology Project, headed by University of California, Berkeley, astronomer Saul Perlmutter, and the High-Z Supernova Search Team, led by Brian Schmidt of the Mt. Stromlo and Siding Spring Observatory in Australia, were doing. Both research teams found the most distant supernovae were fainter than their distances would imply.

The only way this makes sense is if the expansion of the universe is speeding up. Gravity works to slow down the expansion, and did so successfully for billions of years. But it now appears we have entered an era where gravity is no match for the mysterious force causing the expansion to accelerate.

The force may take the form of dark energy, quintessence, the cosmological constant, or some other strange name with a different effect. But the results of this energy — which makes up 73 percent of the mass-energy content of the cosmos — likely will lead to unending expansion. (Although, some cosmologists say the force doesn't have to last forever.) If it keeps operating as it has, a "Big Rip" may be in our future. If not, a "Big Crunch" could still be ahead.

10 What will **happen** to **life** on **Earth**?

There are few topics of greater interest and intrigue to everyone who has ever contemplated the cosmos. Everyone alive on the planet today, all 6.5 billion of us, has an interest in the question of Earth's habitability — and the approximately 100 billion people who have ever lived on the planet would have been interested in this as well. From an astronomer's viewpoint, the standard feeling about Earth's habitability goes something like this: The Sun is about halfway through its main sequence life, about 4.6 billion years old and with 5 billion years left, so life on Earth should be about halfway through, as well, right?

Wrong. The earliest microfossils, primitive, bacteria-like life, date to about 3.5 billion years ago and come from the northern Australian desert. Such cyanobacteria, or "blue-green algae," are larger than ordinary bacteria and can leave behind fossils that scientists can date radiometrically to high precision. Moreover, these bacteria create stramatolites, dome-shaped structures that grow in aquatic environments and can leave behind fossilized remains. Dating these colonies of microbes gives us our earliest view of life on Earth.

So we know life on Earth has been around for at least 3.5 billion years. Why shouldn't it continue for another 3.5 or even 5 billion years, until the Sun becomes a red giant? In a paper titled "The Goldilocks Problem" in *Annual Review of Astronomy and Astrophysics* in 1994, biologist Michael Rampino of New York University and physicist Ken Caldeira of Lawrence Livermore National Laboratory described how future climatic changes on Earth will adversely affect life. Three significant problems will challenge future life on Earth. And human beings, we must remember, are among the more fragile types of life on the planet, not the hardiest.

First is the looming rise in temperature brought to us by the Sun's increasing radiation output. This will happen long before the Sun swells into a red giant. Second is a decrease in global carbon dioxide, also a result of the Sun's increasing luminosity, that could cut off the influx of carbon into the planet's biosphere. Third will be the gradual loss of water on the planet, and the inevitable depletion of the oceans.

BLUE PLANET. Earth has abundant life because water exists on its surface. When that ceases to be the case, perhaps as soon as a billion years from now, life will perish or have to find another home. NASA

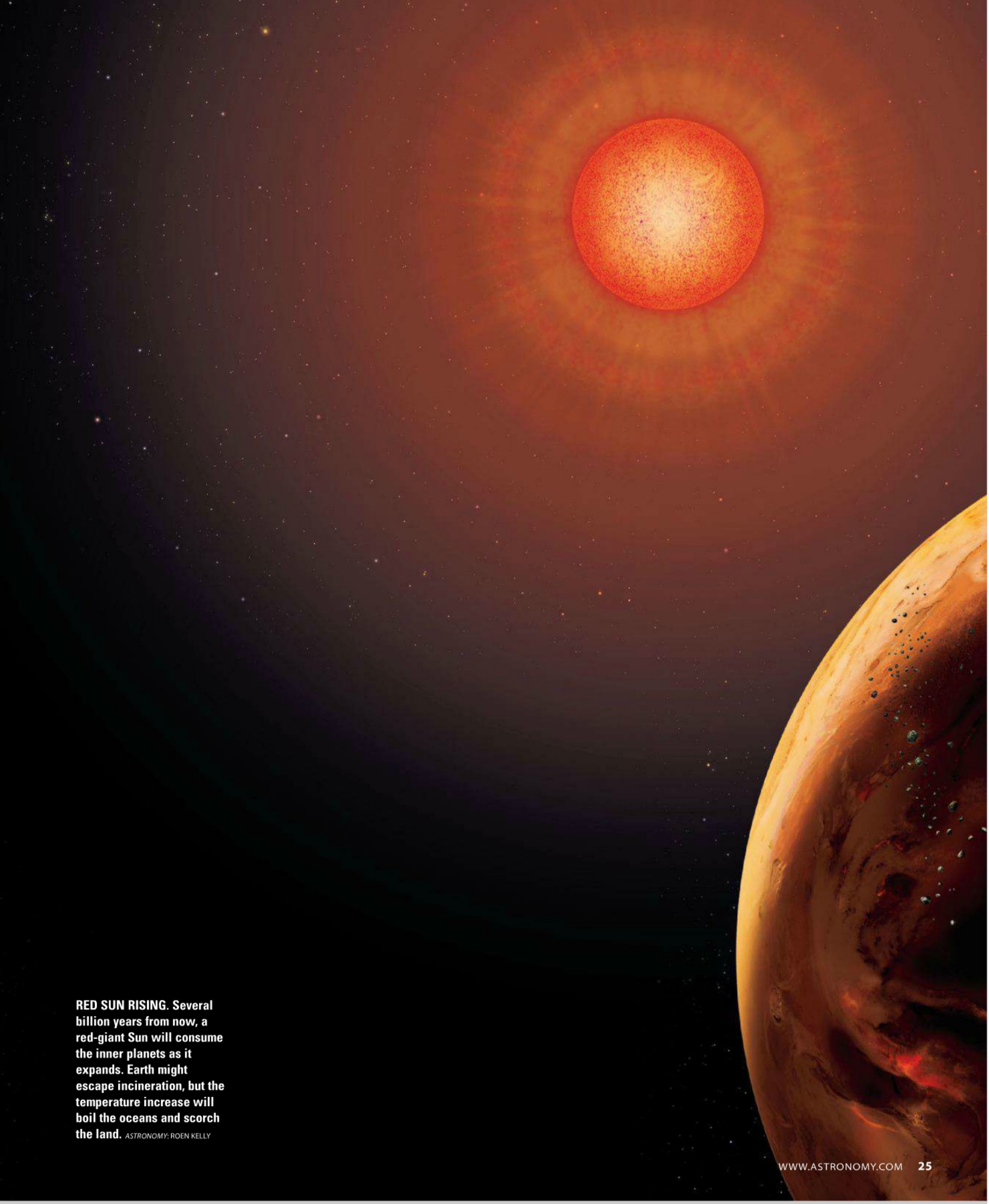
MARCELO BASS/CTIO/NOAO/AURA/NSF

BIG BANG. Life on Earth still may be around a billion years from now, but there's no guarantee. Besides the possibility of a human disaster, a nearby supernova (Supernova 1987A appears near the center of this image) could do us in.

The evaporation of water into the space surrounding Earth will mark the final gasp of any life on the planet. This will occur about 2.5 billion years from now, but the oceans themselves could be mostly gone by 1 billion years into the future — a mere blink of the eye in cosmic terms. The planet's surface temperature will increase dramatically and be too hot for most life, also within a billion years. And the decrease in carbon dioxide and a significant alteration of the atmosphere could take place well before 1 billion years from now.

Considering that life has been on the planet for at least 3.5 billion years, the story of life on our planet could be some 80 percent done — far more than the halfway mark we tend to think of as an analog to our Sun's lifetime. And this simply looks at life's endgame: It does not take into account a host of other mechanisms that could wipe out human civilization.

Killer asteroid or comet impacts, a nearby supernova or gamma-ray burst, global warming, and supervolcanoes are just some of the climate-changing events that could have a catastrophic impact on our planet and life. The universe can be a violent, uncaring place indeed!



RED SUN RISING. Several billion years from now, a red-giant Sun will consume the inner planets as it expands. Earth might escape incineration, but the temperature increase will boil the oceans and scorch the land. *ASTRONOMY*: ROEN KELLY

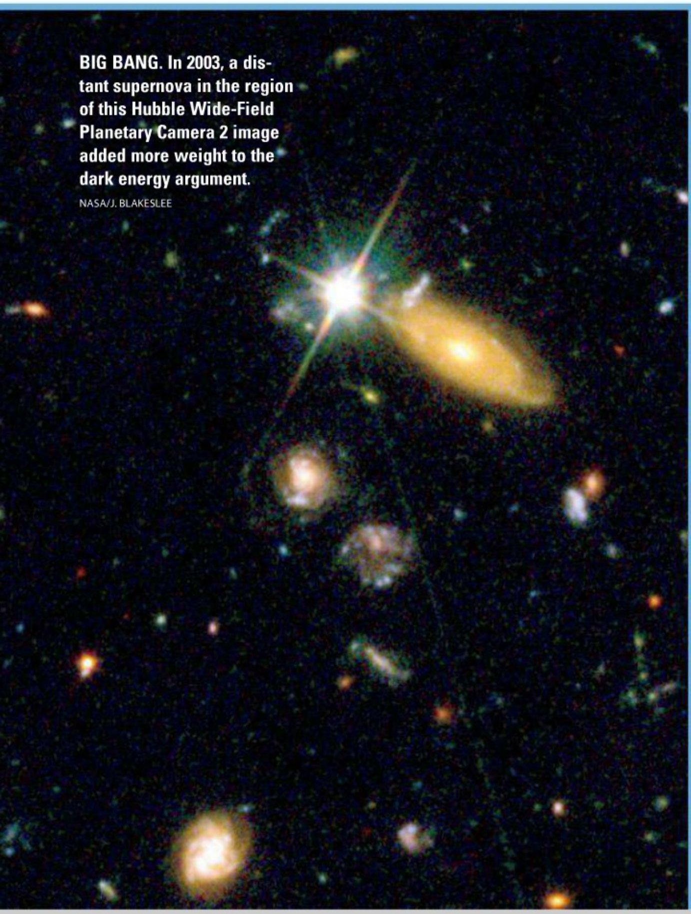
11

What is dark energy?

In a 1998 research breakthrough, Saul Perlmutter of the University of California, Berkeley, and his colleagues in the Supernova Cosmology Project found the expansion rate of the universe is accelerating. Perlmutter and his team made the discovery by observing distant type Ia supernovae, whose brightnesses are well known, at different distances. His team made observations in conjunction with a team led by Brian Warner of the Mt. Stromlo-Siding Spring Observatories. This astonishing finding contradicts conventional wisdom, which suggests the universal expansion rate of galaxies away from each other is constant. Several implications follow the new finding, the most significant of which has turned cosmology on its head.

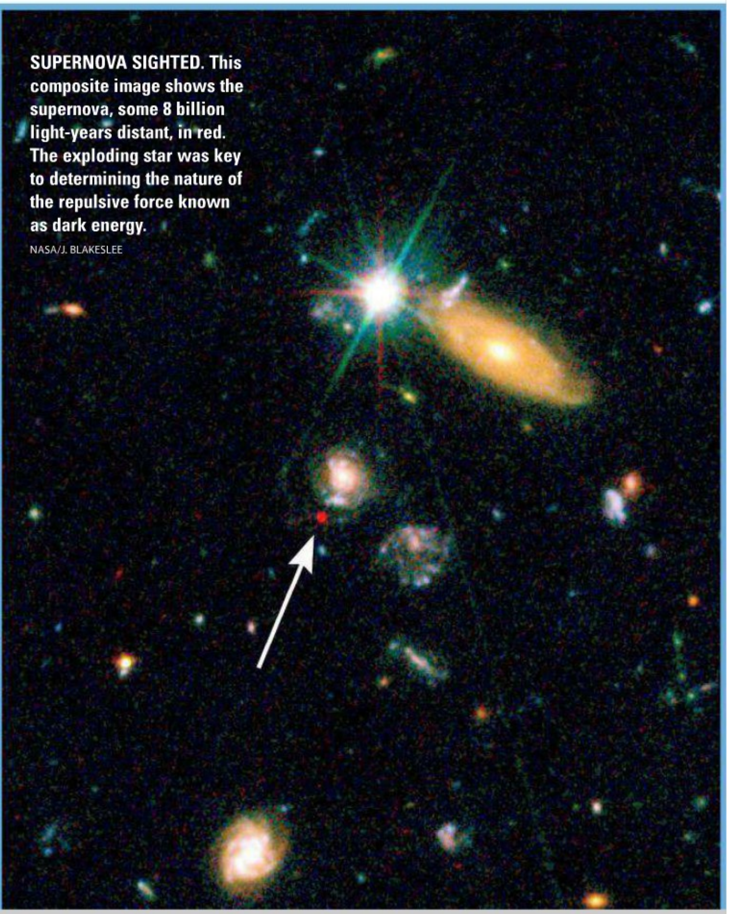
In May 1999, Perlmutter and his colleagues published a paper in *Science* magazine that outlined their ideas about a newly understood force in the universe — dark energy. "The universe is made up mostly of dark matter and dark energy," wrote Perlmutter. Astronomers now think 75 percent of the cosmos consists of this dark energy and that it is the force accelerating the universe's expansion. If dark energy is as dominant as astronomers believe it is, it will eventually force the universe into a cold, dark, ever-expanding end to space and time — the universe will end with a whimper, not with a bang.

Dark energy, now that it is known to exist, has come to the fore as one of science's great mysteries. Although astronomers don't yet know exactly what it is, three leading contenders offer possible explanations. The first is the cosmological constant, or a static field of fixed energy, proposed by Albert Einstein (and which he later declared his biggest blunder). A second possibility is quintessence, a dynamic, scalar field of energy that varies through time and space. The third possibility is that dark energy doesn't exist; what astronomers observe with distant



BIG BANG. In 2003, a distant supernova in the region of this Hubble Wide-Field Planetary Camera 2 image added more weight to the dark energy argument.

NASA/J. BLAKESLEE



SUPERNOVA SIGHTED. This composite image shows the supernova, some 8 billion light-years distant, in red. The exploding star was key to determining the nature of the repulsive force known as dark energy.

NASA/J. BLAKESLEE

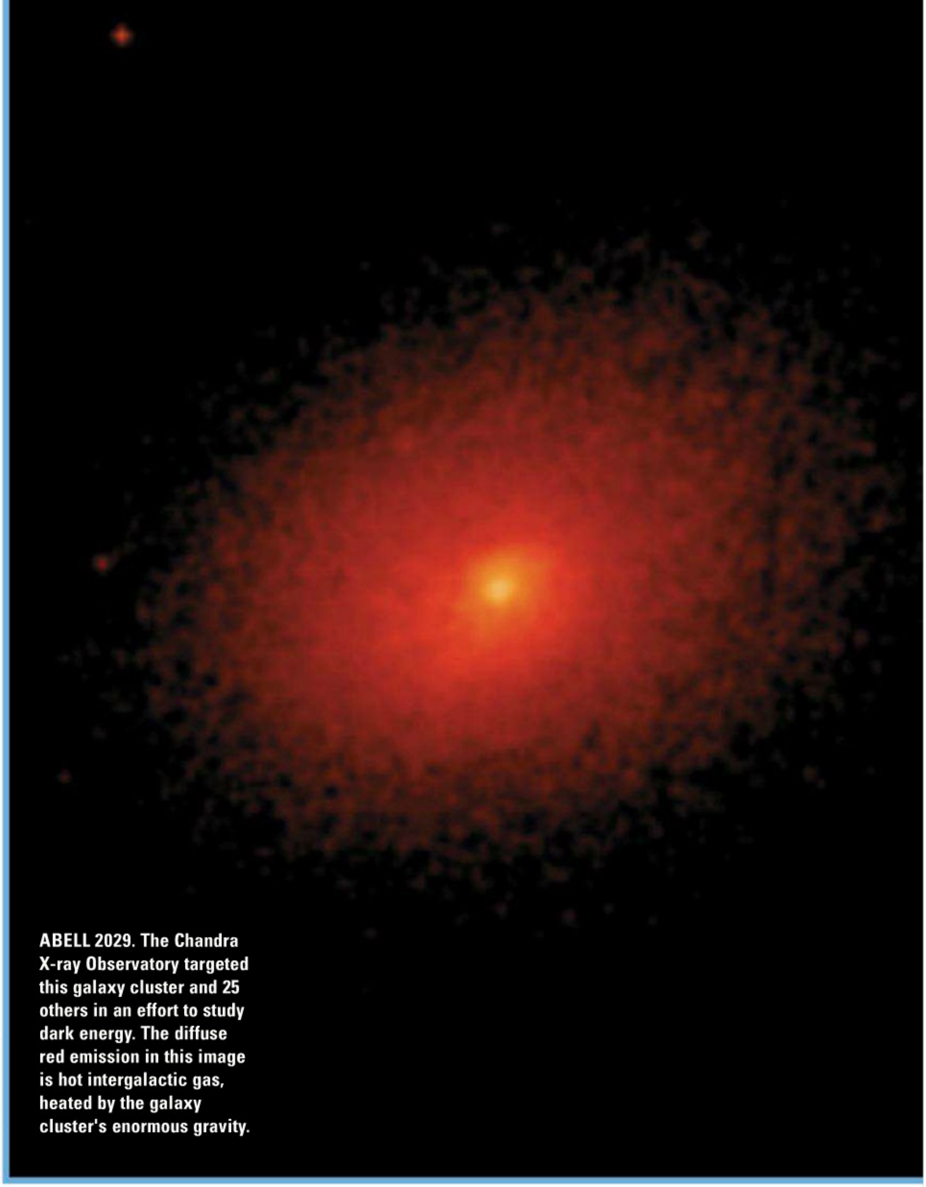
supernovae represents a breakdown of Einsteinian gravitational physics that has yet to be explained. A fourth possibility could be something we don't yet understand.

Determining what dark energy is will be far more complex than the discovery of the accelerating universe. Astronomers are using the Hubble Space Telescope to "push back to higher redshifts to measure the onset of acceleration," says Adam Riess of the Space Telescope Science Institute in Baltimore. One important moment to focus on is the so-called transition point, the time when dark-energy acceleration overtook the normal pull of gravity and became the dominant force in the universe. This probably happened about 5 billion years ago, according to Riess.

Research on type Ia supernovae must continue to get a handle on this question. Could the reliability of type Ia supernovae come into question? The fact that not as many heavy metals existed in the very early universe could influence the brightnesses of these objects and throw astronomers' observations off the mark.

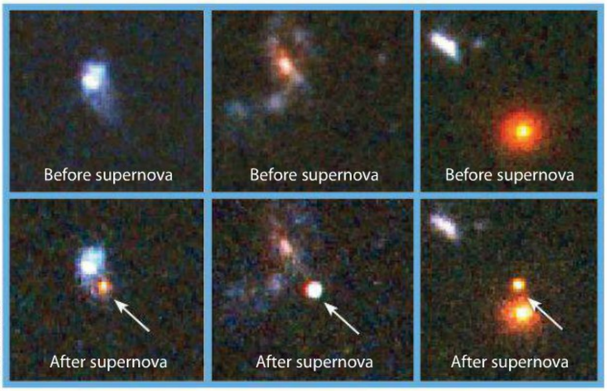
Other techniques will also come into play. Astronomers will observe galaxy clusters to see how their densities vary with distance. This could relate to whether gravity or dark energy dominated at certain times in the cosmos' past. Cosmologists will also study gravitational lenses for clues to dark energy's existence in the distortion patterns visible in these optical illusions. This pioneering technique, developed by the University of Pennsylvania's Gary Bernstein, is in its infancy. "Right now," says Bernstein, "we're just starting to measure dark energy, but the more galaxies we get, the better we'll do. The goal is to see as much sky as possible."

The era of dark energy has just begun. Although no one yet knows what it is, astronomers think it represents an essential part of understanding the universe. Vast amounts of research will focus on dark energy in the years to come.



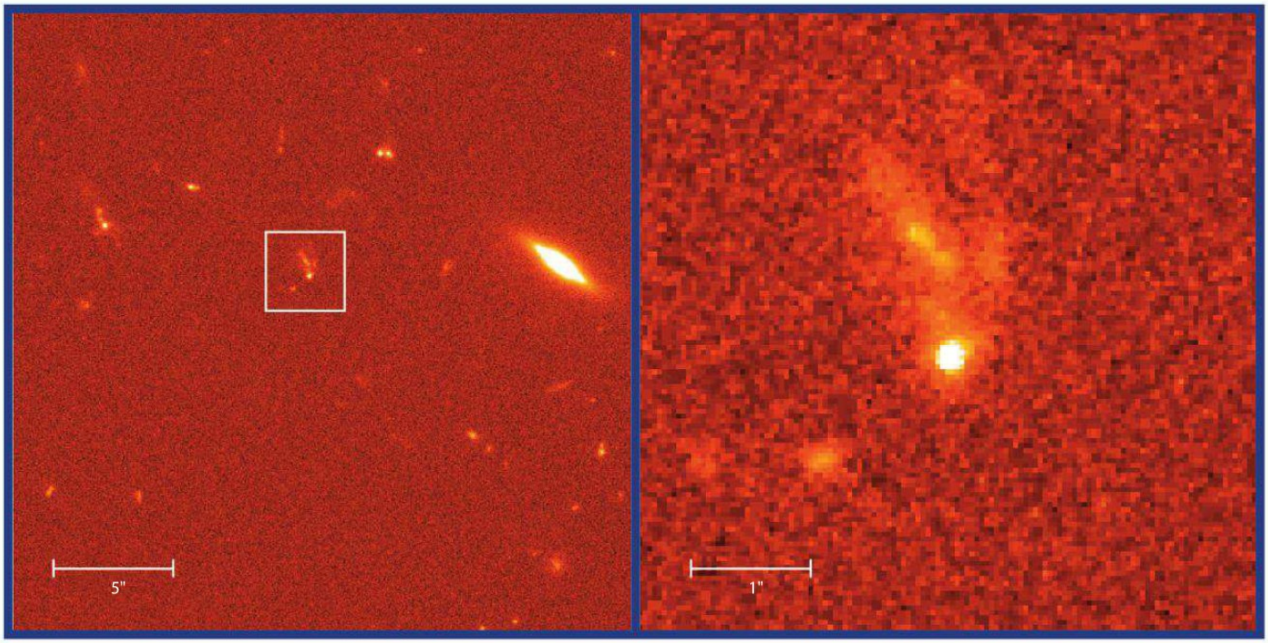
ABELL 2029. The Chandra X-ray Observatory targeted this galaxy cluster and 25 others in an effort to study dark energy. The diffuse red emission in this image is hot intergalactic gas, heated by the galaxy cluster's enormous gravity.

NASA/CXC/IoA/S. ALLEN ET AL.



DARK SECRETS. Three of the most distant supernovae known, imaged by the Hubble Space Telescope, help reveal secrets about dark energy. The stars exploded when the universe was half its current age. By measuring the expansion rate of the cosmos carefully, astronomers can see that a mysterious dark force has pushed space apart.

NASA/ADAM RIESS



ANDREW FRUCHTER/NASA

DISTANT BOOM. On January 23, 1999, an intense gamma-ray burst exploded with the energy of 100 million billion stars. Hubble's camera caught the interloper in a galaxy two-thirds of the way to the edge of the visible universe.

12

What are gamma-ray bursts?

One of the greatest mysteries of observational astronomy during the past 3 decades has been the nature of gamma-ray bursts (GRBs). The most powerful blasts in the cosmos, these flashes of light randomly appear throughout the sky every day, giving astronomers few clues about the origins of these elusive bursts.

Some GRBs last for only a fraction of a second — some as long as a minute — and beam so much energy in a focused searchlight that they make even supernovae appear weak in comparison. The longstanding mystery of gamma-ray bursts — are they powerful events in our Milky Way Galaxy or super-powerful events beyond it? — is now heading toward resolution.

HETE-2 showed GRB 030329 to be 2.6 billion light-years away.

The key to unraveling the nature of gamma-ray bursts comes in part from the discovery that they are narrowly focused beams. This realization allowed astronomers to estimate energies for individual bursts and hypothesize the number of total bursts occurring over a given time interval. "If you didn't know the geometry," says Shri Kulkarni of the California Institute of Technology, "and assumed spherical emission when it's really conical, you could infer an energy release 1,000 times bigger than it really is. And if the beams are as narrow as we think they are, for every GRB I see, there are 1,000 I don't see."

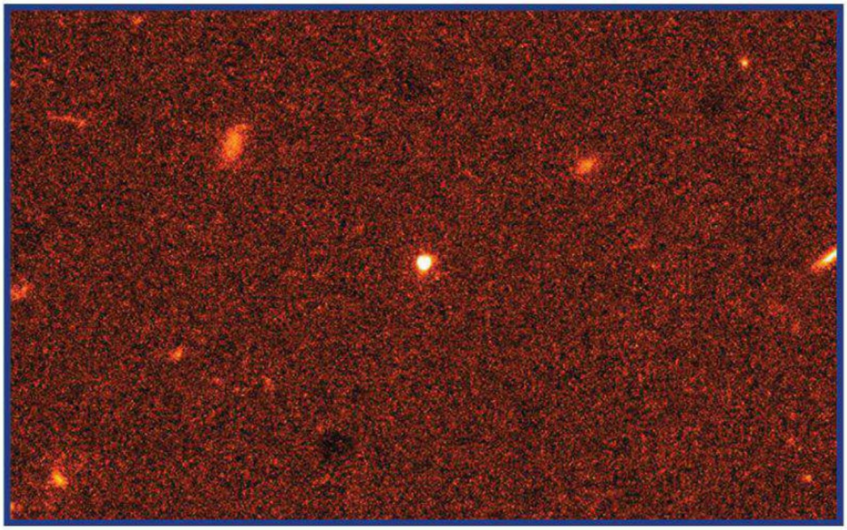
A key moment in researching gamma-ray bursts occurred suddenly March 29, 2003, when a brilliant burst in the constellation Leo appeared in the data collectors of NASA's High Energy and Transient Explorer (HETE-2) satellite. By immediately capturing the burst and its afterglow, HETE-2 showed GRB 030329 to be 2.6 billion light-years away and revealed its association with a bright supernova that exploded at the same time. This led researchers to link the most common type of GRB, those lasting 20 seconds or longer, with the collapse of massive stars about 30 or more times larger than the Sun. The stars go supernova and create powerful black holes in the process.

The next big step came in November 2004, when NASA launched the Swift Gamma-Ray-Burst Mission. The Swift satellite has orbited Earth since, observing gamma-ray bursts. Almost a year later, in October 2005, astronomers using Swift solved the 35-year-old mystery of one class of gamma-ray bursts known as short bursts, those lasting just a few milliseconds. What could produce enough radiation to equal that of a billion Suns in such a short period?

On May 9, 2005, Swift detected a short burst, marking the first time for a short burst that astronomers detected an afterglow — something more common with longer bursts. “We had a hunch that short gamma-ray bursts came from a neutron star crashing into a black hole or another neutron star, but these new detections leave no doubt,” says Derek Fox, an astronomer at Pennsylvania State University. Fox’s team discovered the afterglow with NASA’s Chandra X-ray telescope. The afterglow was also observed by a team led by Jens Hjorth of the University of Copenhagen, using the Danish 1.5m telescope at La Silla Observatory in Chile.

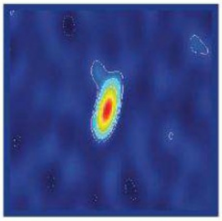
Another gamma-ray burst was spotted July 9 with HETE-2. According to George Ricker of MIT, “The July 9 burst was like the dog that didn’t bark. Powerful telescopes detected no supernova as the gamma-ray burst faded, arguing against the explosion of a massive star. Also, the July 9 burst, and probably the May 9 burst, are located in the outskirts of their host galaxies, just where old merging binaries are expected.”

So after 35 years, a key piece of the puzzle about gamma-ray bursts appears solved. Astronomers do not yet know the details of how these incredibly energetic objects work, but they know the causes of many such bursts. Over the coming months and years, Swift, HETE-2, and other instruments will further refine the picture until it becomes crystal clear — an exciting moment in science.



K. SAHU/M. LIVIO/L. PETRO/D. MACCHETTO/NASA

▲ **MATCH GAME.** **Are gamma-ray bursts common in normal galaxies? In 1997, Hubble’s Wide Field Planetary Camera 2 captured GRB 970228's visible glow, the first that linked a gamma-ray burst with a specific host galaxy. Astronomers estimate the GRB’s host galaxy’s redshift is 0.835, which corresponds to a distance of hundreds of millions of light-years.**



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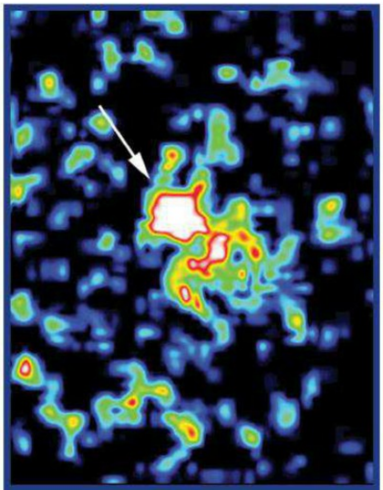
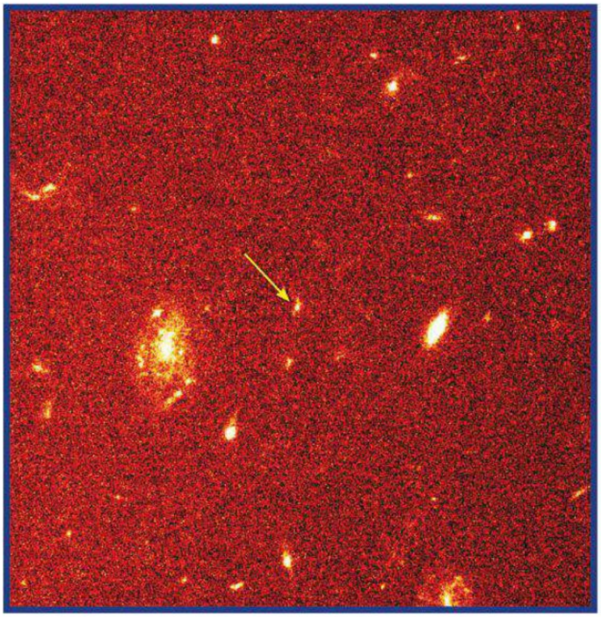
▲ **CLOSE BURST.** **In 2003, the VLBA snapped this radio image of 2.6 billion light-years-distant GRB 030329.**



ELENA PIAN/ANDREW FRUCHTER/NASA

LONE FLASH. On May 8, 1997, Hubble caught the visible fireball from a distant gamma-ray burst that doesn’t appear to be surrounded by a host galaxy.



S. R. KULKARNI AND S. G. DJORGOVSKI/THE CALTECH GRB TEAM/NASA

◀ **RECORD BURST.** **In 1997, astronomers using the Hubble Space Telescope imaged a gamma-ray burst that was briefly as bright as the rest of the universe. GRB 971214, which lies about 12 billion light-years away, released 100 times more energy than astronomers previously thought possible.**

13

Will asteroids threaten life on Earth?

The solar system's history is riddled with violent impacts. One good look at the Moon through a small telescope shows that. Whereas the airless Moon preserves its ancient cratering record almost perfectly, planets like Earth — with wind, water, and erosion — slowly cover the ravages of time.

Although a barrage of large impacts occurred early in the solar system's history, a time referred to as the heavy bombardment era, significant impacts rocked Earth's terrain in geologically recent times. For example, the K-T impact in the Yucatan Peninsula some 65 million years ago witnessed a 6-mile-wide (10 kilometers) asteroid striking Earth. That's large enough to create a firestorm of hot debris. Falling back through Earth's atmosphere, the debris ignited enormous fires and choked out most life.

Even a smaller air-blast over Siberia in 1908, which occurred along the Tunguska River, felled 60 million trees over an area of more than 1,330 square miles (2,150 square kilometers). If the explosion had occurred near a populated city, the results would have been catastrophic.

Although most inner orbital debris was cleared out during our solar system's early days, a huge population of near-Earth objects (NEOs) is still out there.

"Nature is blindly throwing rocks at our planet," says astronomer Bill Cooke of NASA's Marshall Space Flight Center in Huntsville, Alabama, "and once every great while manages to score a hit." Of course the population of small objects is much larger than that of big ones, so small objects strike Earth more frequently. To find out how often our planet is struck, astronomers study the record of mass extinctions, the orbits of NEOs, and records of explosions in Earth's upper atmosphere. Satellites record the amount of heat released from NEOs that explode in Earth's atmosphere. Data from atmospheric explosions during the past 30 years show meteoroids erupting in the atmosphere produce at least one 5-kiloton explosion each year.

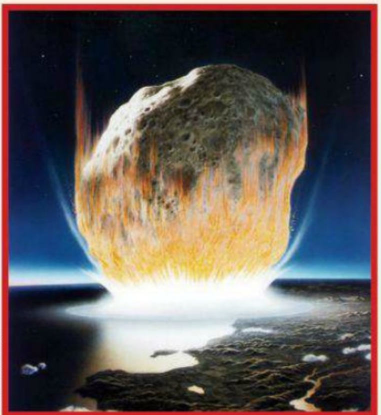
The destructive power a rock carries to Earth is directly proportional to its size.

Scientists expect about one hundred 300-foot-wide (100 meters) objects will strike Earth over the next million years, while during that same time interval, two 0.6-mile-wide (1 km) objects will hit. It's these larger objects that, like the K-T impactor, pose a threat to civilization.

The destructive power a rock carries to Earth is directly proportional to its size. A 0.6-mile-wide rock, which strikes Earth every few million years, delivers a blow equivalent to 20,000 megatons of TNT. An asteroid only 300 feet across, however, can strike every 1,000 years and hit us with a 20-megaton explosion. "Put into more meaningful terms," says Cooke, "a person living to the age of 100 has about a 1-in-10 chance of a 10-megaton Tunguska-like impact occurring somewhere on Earth at some time during his or her life. Of course, the odds of being hurt by such an event are vastly lower — by roughly a factor of 50,000 — because the asteroid would have to strike nearby to cause injury."

USGS

BATTERED SPUD. On October 29, 1991, the Galileo spacecraft imaged the asteroid 951 Gaspra. The potato-shaped body measures about 12 by 8 by 7 miles (20 by 13 by 11 kilometers). More than 600 craters on its surface each span 300 to 1,500 feet (90 to 460 meters).



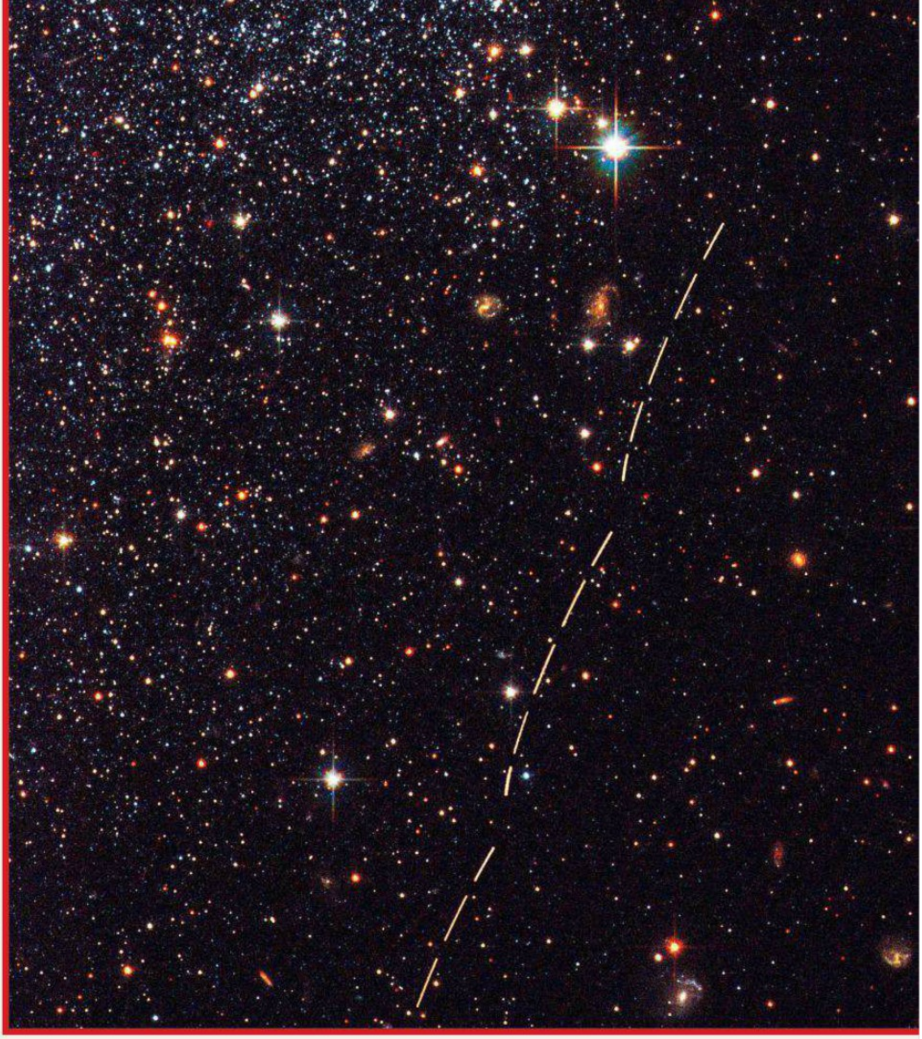
NASA/DON DAVIS

DANGEROUS ROCKS. Even a small asteroid striking Earth would have catastrophic regional consequences. A half-mile-wide asteroid impact would have global consequences. A 6-mile-wide (10 km) or larger asteroid impact could wipe out civilization.

Given the potential danger to the human race, aggressive NEO discovery programs are underway, led by LINEAR, the Lincoln Near-Earth Asteroid Research program located at White Sands Missile Range in New Mexico. Together with other surveys, the collective Spaceguard program aims to identify 90 percent of all NEOs larger than 0.6 mile across by 2008. The new-object discovery rate is astounding: About a dozen new objects were found in 1995; by 2004, the number had increased to nearly 500.

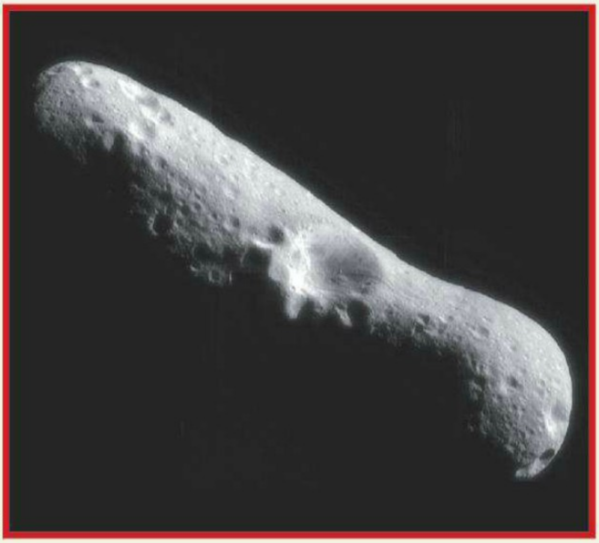
After finding NEOs, the real challenge is to identify their orbits and project them forward to predict possible impacts. New discoveries are forwarded to the Minor Planet Center in Cambridge, Massachusetts, where planetary scientists calculate orbits and publish the results.

Because humans now have the technology to find and observe NEOs doesn't mean the historical record of Earth impacts will change. What should we do when we find an object that will strike our planet? Given enough time, scientists could send a spacecraft carrying a charge that would detonate near the asteroid and nudge it out of its Earth-impacting orbit. But if a long-period comet were headed toward us, we would have little notice. We would have to duck, cover, and hope for the best. ▣



STScI

▲ **WANDERING STAR.** As the Hubble Space Telescope imaged the Sagittarius Dwarf Elliptical Galaxy in August 2003, the wandering light trail of an asteroid interrupted the exposure. Because the camera's shutter intermittently closed, a series of arcs appears rather than a continuous line.



NASA

◀ **ASTEROID CLOSE-UP.** Minor planet 433 Eros, shot by the NEAR-Shoemaker spacecraft February 14, 2000, reveals details of the asteroid's battered surface. Eros spans 20 by 8 by 8 miles (32 by 13 by 13 kilometers). The prominent crater at center is 4 miles (6 km) wide.

14 Is water necessary for life?

Water drives NASA's solar-system exploration program. Wherever there's a chance water could exist, either as liquid or ice — like on Mars, Jupiter's moon Europa, and Saturn's moon Enceladus — future exploration will be a focus for scientists.

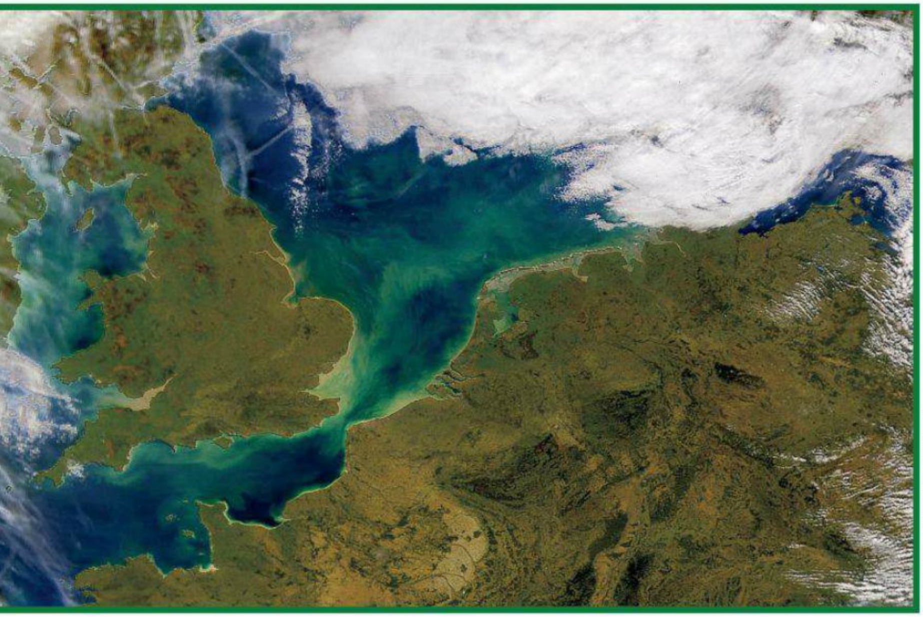
This works for planetary-exploration missions and for proposed extrasolar-planet telescopes like the Terrestrial Planet Finder and Kepler. For many years, planetary scientists and biologists have held fast to one maxim: Water is essential for life. Great interest focuses on the possibility of extraterrestrial life, even if it's merely microbial. So, follow the water to find where the big planetary-exploration dollars will be spent.

The seed of finding extrasolar life where there's water goes back to Harvard biologist Lawrence Henderson, who wrote in his 1913 work *The Fitness of the Environment*, "Life necessarily must be based on carbon and water, and have its higher forms metabolizing free oxygen." For decades, scientists took this statement as gospel, but it was questioned in the 1970s. Carl Sagan wrote he doubted it "because Lawrence Henderson was made of carbon and water and metabolized free oxygen. Henderson had a vested interest."

Life in the universe, astronomers and biologists now admit, could be based on completely different chemical systems than ours. The first thing to do is to define what we mean by "life."

By definition, living things have several properties that separate them from rocks and dirt. Living things on Earth are arranged into cells. They are also highly organized, on different levels and with different tasks. They take in energy from the environment and excrete waste products. They exhibit homeostasis, stable internal conditions that are required to stay alive. They grow and change, showing differentiation and mutation. They also reproduce, passing genetic material to their descendants. Anything in the universe that exhibits these characteristics would be considered a living being.

The movement of molecules plays a key part in making a place hospitable for life. A flowing solvent can trigger molecule movement and, thus, the energy reactions life requires to take in energy and excrete waste. On Earth, that solvent is water. But water may not be the molecule-moving solvent everywhere in the universe. Clues to alternative environments have come from strange places as well as from our own familiar


SEAWIFS PROJECT, NASA/GSFC/ORBIMAGE

LIFE FROM ORBIT. **This incredible image from space shows evidence of life in water. Taken October 28, 1997, with the SeaWiFS instrument on the SeaStar spacecraft while in low-Earth orbit, the image shows a phytoplankton bloom (blue-green) in the English Channel.**

NASA/JPL/MALIN SPACE SCIENCE SYSTEMS

LIQUID MARS. A 2003 image made with the Mars Global Surveyor spacecraft shows evidence of large amounts of flowing water on ancient Mars. Sediments carried by water over long periods of time formed ridges of layered rock.

planet. On Earth, microbes can remain alive in the absence of water nearly indefinitely. They go dormant, take in no energy, and do not reproduce or grow. Yet, microbes can revive and become active again at a much later date.

If liquids other than water might help create and sustain life, which ones might they be? Water does have an amazing number of properties that help support life. But could another fluid — ammonia, methane, formamide, or sulfuric acid — create a place where exotic life forms could flourish?

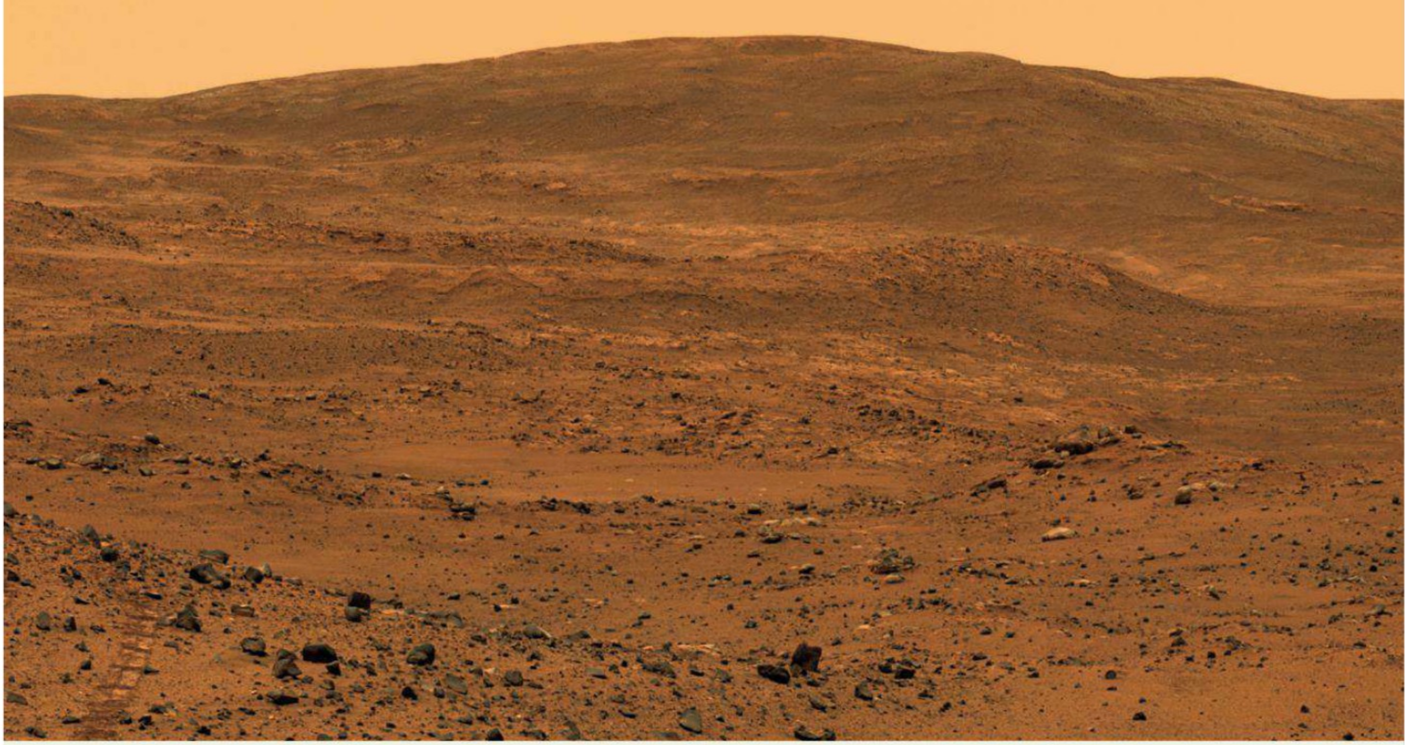
On Earth, microbes can remain alive in the absence of water nearly indefinitely.

At Saturn's large moon Titan, the Huygens probe discovered signs of abundant liquid methane that acts as Titan's "water." It also found abundant ethane. There is no evidence of life on Titan, and Huygens was not designed to detect it; however, some scientists speculate self-replicating molecules might exist in Titan's methane-rich environment or may have even produced some of it.

The biggest challenge is to extend the search for life to extrasolar planetary systems. "Right now, we can barely analyze the atmospheres of the giant planets in our solar system," says Christopher Chyba, a planetary scientist at Stanford University. "We're probably decades away from being able to do that for planets around other stars."

Is water needed for life, or could other solvents do? That's the key question, but it ties in to another, even larger one: Does extraterrestrial life exist in the universe? With at least 200 billion stars in our galaxy and 125 billion galaxies in the universe, life has plenty of places to gain a foothold. There are also plenty of opportunities for life to flourish based on solvents other than water. ■

LIFE'S BIG POOL. Earth's watery surface is perfect for sustaining life, even with such fearsome recurring events as hurricanes. Astronauts aboard the ISS imaged the massive storm Ivan September 11, 2004. NASA

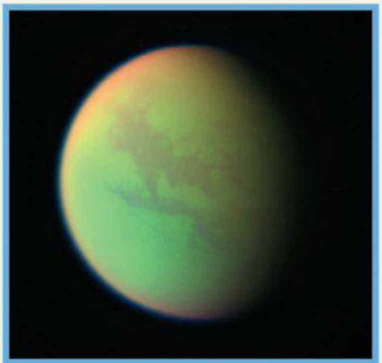


STERILE RED PLANET? Aside from a controversial meteorite from Mars, no evidence of life, microbial or otherwise, exists for the Red Planet. Only when spacecraft are able to dig into subsurface aquifers will planetary scientists answer the question.

15

Is there **life** on **Mars, Titan,** or **Europa**?

Mars has been a target of speculation about extraterrestrial life for more than 200 years, ever since observers tracked the seasonal growth and decay of the planet's polar ice caps.



NASA/JPL-CALTECH

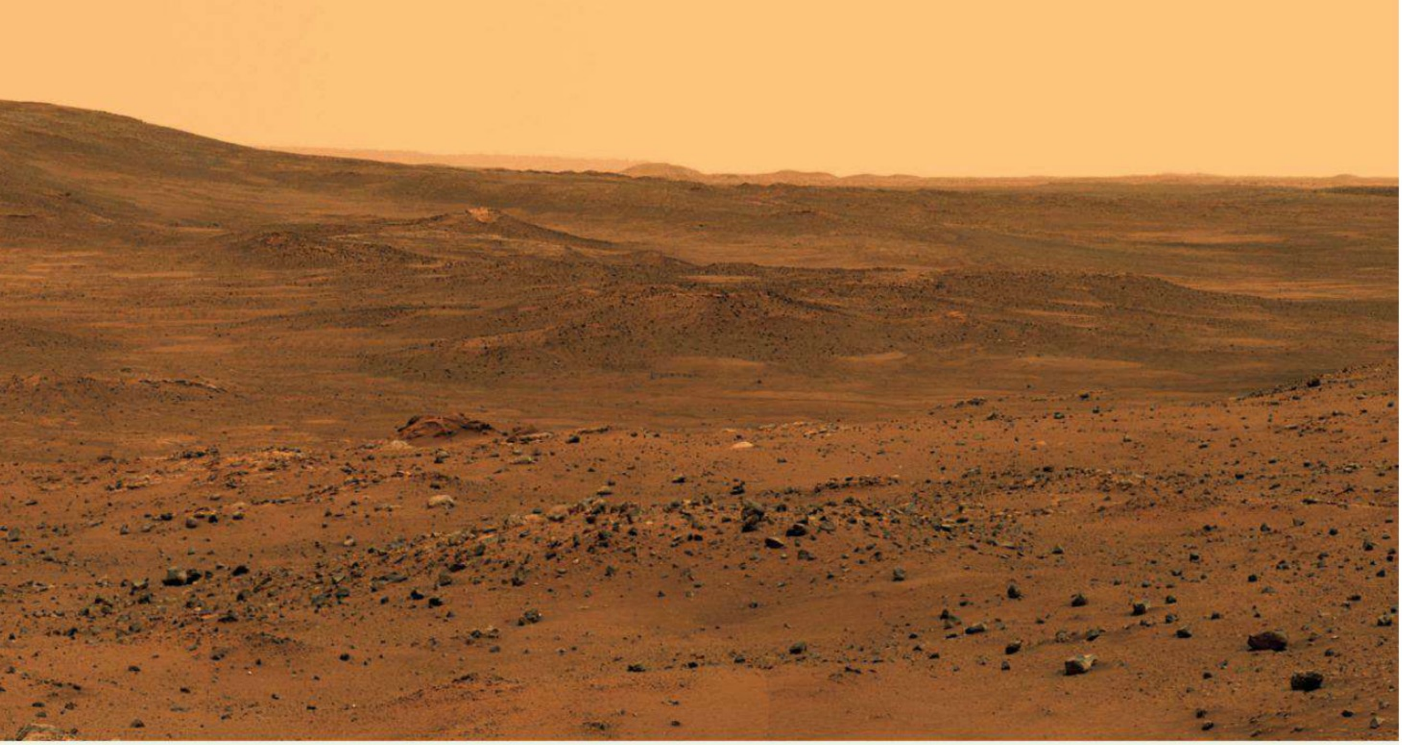
HAZY SHADE OF METHANE. Saturn's largest moon, Titan, has a thick atmosphere where methane forms a hazy layer. Lower in the atmosphere, Titan has a thick smog of complex organic molecules, the building blocks of life.

Fevered speculation about martian life raged in the late 19th century, when British astronomer William Whewell (and later, American astronomer Percival Lowell) proposed a virtual civilization on Mars. Lowell based his claim on flawed observations of "canals" he made at Lowell Observatory in Arizona. The Victorian momentum for a martian civilization led H. G. Wells to write *War of the Worlds*, in which martians, faced with a planet that was drying out, were forced to seize Earth.

However, no evidence for life on Mars has ever come to light. In 1965, the Mariner 4 spacecraft dashed the hopes of pro-martians when it revealed an arid, stark landscape in the first close-up images.

When the Viking landers analyzed martian soil in 1976, their results on finding traces of life were inconclusive. Observations in the 1990s by the Mars Global Surveyor demonstrated the planet's lack of a cohesive magnetic field, which allows cosmic radiation to bombard the planet's surface. With no protective magnetic field, much of Mars' atmosphere dissipated into the solar wind, leaving a cold, arid desert that would be extremely hostile to life.

A media frenzy over martian life occurred in 1996, when scientists announced they had found suspicious, bacterialike structures in martian meteorite ALH 84001. This hand-sized meteorite, plucked from Antarctic ice in



NASA/JPL-CALTECH/CORNELL

1984, showed wormlike structures measuring only 100 nanometers in diameter. NASA astrobiologist David McKay conjectured the structures were possible bacteria from Mars. After years of debate, however, the evidence seems inconclusive at best, and most scientists believe the lines are chemical structures not indicative of living organisms.

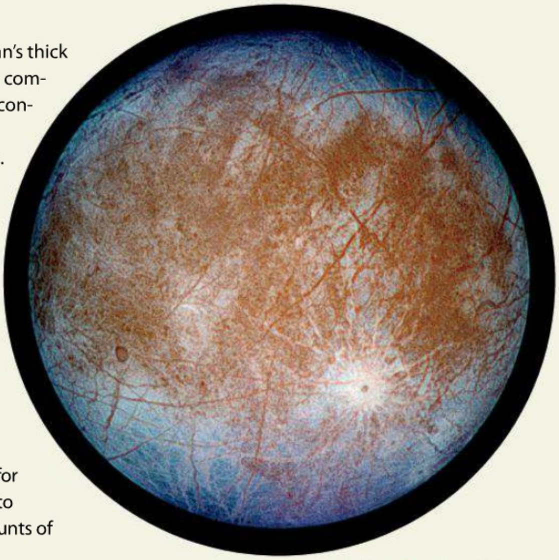
All this does not necessarily add up to a lifeless Mars, however. Recent spacecraft missions have shown evidence of abundant flowing water on Mars in its past. Planetary scientists believe the Red Planet likely also has subsurface aquifers that contain vast amounts of the liquid, as well as water ice scattered in places on the surface.

The Spirit and Opportunity Mars rovers demonstrated in 2004 that Mars clearly had a wet past. And where there's water, there could be life. The amounts of methane and formaldehyde discovered on Mars are more than planetary scientists would think could exist, given the planet's atmosphere. Could extremophiles, microbial life forms existing somewhere inside the planet, be producing these gases?

Another intriguing possibility for life elsewhere in the solar system could be on Titan, Saturn's largest moon. Larger than the planet Mercury, Titan is the only moon with a substantial atmosphere. Titan's thick atmosphere abounds with organic compounds. Although its atmosphere consists mainly of nitrogen, it also contains vast amounts of methane.

On Earth, methane is a byproduct of living organisms. Titan is a hostile place for living organisms, with temperatures too cold for water to exist in liquid form. Could it have been different in the past? Might a huge impact on Titan have delivered enough heat to liquefy water for a time and sustain the development of primitive life? Although planetary scientists think Titan is an unlikely place for life to exist now, they will continue to investigate the curiously large amounts of methane in its atmosphere.

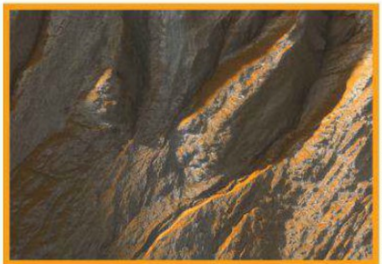
What about life on Europa? The smallest of Jupiter's four Galilean moons is an intriguing possibility. The moon's smooth, icy surface is not at issue here — it's the liquid ocean that scientists know exists under its surface. The Galileo spacecraft observed a weak magnetic field that varies as Europa passes through Jupiter's strong magnetic field. This suggests Europa harbors a subsurface ocean of salty water. Planetary scientists believe microbes could exist in this ocean the same way they do around hydrothermal vents in Earth's oceans. Future exploration missions, such as NASA's hydrobot concept, would attempt to release a probe into the Europan ocean to explore it for signs of life. ■



COOL REPOSITORY. **Europa, Jupiter's sizeable moon, has a slushy liquid ocean beneath its icy crust. Could the watery vault hold microorganisms?** NASA/JPL/SSI

16

Why did **Mars dry out?**

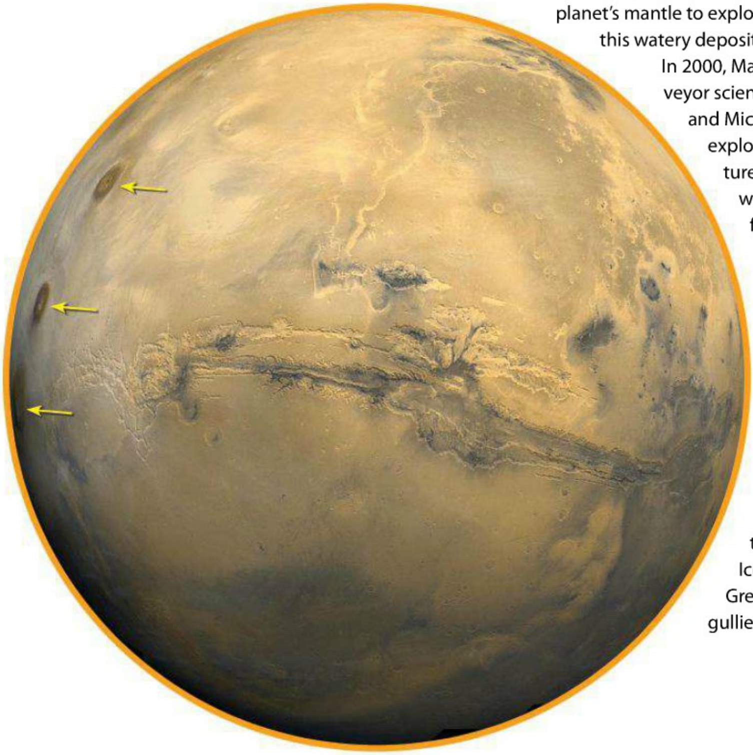


DRY GULLIES. These gullies in Mars' Terra Sirenum region suggest liquids once flowed on the Red Planet.

NASA/JPL/UNIV. OF ARIZONA

Years ago, astronomers detected signs of Mars' watery past. Early evidence came from imaging large numbers of winding channels on the Red Planet. These images suggest abundant liquids of some type flowed on the planet at some point in its history. In 1972, the Mariner 9 spacecraft orbited Mars and took photos of what appear to be dry riverbeds scattered over the planet's surface.

More recently, Tim Parker of the California Institute of Technology suggested many dry lakebeds also exist on Mars — although this interpretation is not as clear as that of the riverbeds. Parker also interpreted some features as ancient shorelines, and even some as basins once filled by lakes. Many of the features Parker interpreted and some of the river channels are scarred by craters, suggesting the Red Planet's watery past had concluded by about 3.5 billion years ago.



COLD AND DRY. A mosaic highlighting Mars' Valles Marineris, the solar system's largest canyon, comprises 102 Viking orbiter images. Three Tharsis-area volcanoes are visible in the picture (arrows). In this volcanic region and others, clear evidence of liquid water on the martian surface appears. NASA/JPL/USGS

The clear implication is that Mars had a watery past and, for some reason, dried out, but not completely. Using images from the Mars Global Surveyor satellite, planetary scientists Devon Burr, Alfred McEwen, and colleagues looked carefully at Marte Vallis, a river channel that extends from Elysium Planitia into Amazonis Planitia.

Freshly sculpted features and a lack of craters indicate this river system harbored water in the last 40 million years. Astronomers believe a significant amount of water lies locked inside underground martian aquifers. Future explorers will drill into the planet's mantle to explore the nature of this watery deposit.

In 2000, Mars Global Surveyor scientists Ken Edgett and Michael Malin explored another feature that suggests a water-laden past for Mars. Edgett and Malin identified numerous "gullies" extending from rocky outcrop highlands to lower portions of hills. They appear to be analogs to features in Canada, Iceland, and Greenland, where gullies form when water saturates the ground and then flows downward. If these martian features were formed by water, the implication is rather amazing in that large flows of water must have happened recently — and maybe even still go on today. The mysterious source of such flowing water might be ice that suddenly melts. The flows would have to be significant to leave surface features because the temperatures and pressures on Mars' surface today mean water quickly evaporates once it reaches the surface.

So if Mars was wet and, therefore, also relatively warm in the past, why did it dry out? Planetary scientists don't yet know, but data from the Mars Exploration Rovers and Mars Express suggest a substantial climate change occurred some 600 million years after the planet's formation. One study released in 2006 by French astrophysicist Jean-Pierre Bibring suggests volcanic eruptions drove Mars' changing climate. By studying the mineralogy of gypsum and hematite on the martian surface, Bibring and his colleagues found evidence of a heavy period of volcanism.

If life did gain a toehold on Mars by this point, the climatic change may have shifted the planet to a less hospitable place. Moreover, Mars cooled following this period of volcanism. During the cooling, astronomers believe Mars' magnetic field dissipated because the planet's molten iron core solidified. When the Red Planet's protective shield no longer sheltered living creatures, the solar wind may have stripped away much of the martian atmosphere and sent much of the planet's water into space. After a rather earthlike start, Mars may have — on a planetary timescale — suddenly turned cold, dry, and hostile to living things.

NASA

CLOSE NEIGHBOR. **The Moon looms large in this view of the lunar disk, shot in January 2003 during space shuttle Columbia's final mission.**

17

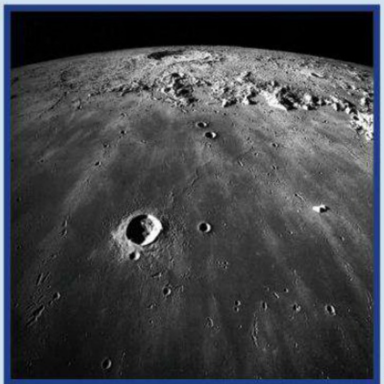
How did the **Moon form?**

Our planet is a strange one, judging by the standards of our solar system. It's the only one with lots of liquid water. But there's a much weirder aspect to Earth — the Moon is huge relative to its nearest neighbor. Look at Venus with no moons, Mars with its two tiny potato-shaped moons, and Mercury with no moon. Earth is special in the solar system because it has such a large moon. Pluto also has a moon, Charon, that's large compared with its host planet.

For many years, planetary scientists struggled with ideas about the Moon's origin. Their ideas included "co-accretion," in which Earth and the Moon formed independently and then came together gravitationally; "capture," in which Earth gravitationally dragged the Moon into orbit after its formation and a near-miss encounter; and "fission," in which Earth's interior belched out the Moon like the splitting of a cell. None of these ideas fully convinced astronomers or matched up with what planetary scientists knew about the Earth-Moon system.

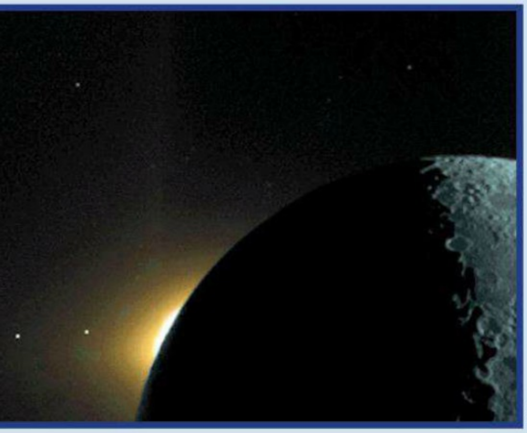
The Apollo missions to the Moon revolutionized thinking about our nearest celestial neighbor. Apollo astronauts found that oxygen isotopes in Moon rocks are similar to those on Earth, indicating the

SMACKDOWN. **Evidence suggests the Moon formed when a giant object collided with the proto-Earth several billion years ago, liberating material that then coalesced into the Moon. The Clementine spacecraft shot this enhanced-color Moon image in 1992.** NASA



NASA

LUNAR LANDSCAPE. An oblique view across Mare Imbrium shows the 58-mile-wide (93 kilometers) Copernicus Crater in the distance. Several small chains of craters, oriented toward Copernicus, show where splashes of material from the Copernicus impact landed. Apollo 17 astronauts made this photo in 1972.



NASA

STRING OF PLANETS. **Planets strung along the ecliptic peek out behind the Moon's disk in an image captured by the Clementine spacecraft. The Sun's corona rises above the Moon's limb, while Saturn, Mars, and Mercury (left to right) lie next to the Sun.**

Moon and Earth formed in the same region of the solar system.

The Moon also is devoid of volatile elements that melt at high temperatures, suggesting it had a very hot birth. Oddly, the more scientists found out about the Moon's rocks, the more the rocks appeared to resemble Earth's mantle — the outer shell of rock on our planet. But Earth's mantle emerged from the more metallic, denser core when our planet formed. How could rocks from the Moon, a separate body, resemble the material in Earth's mantle?

The clues to a solution came from an unexpected direction. Apollo 11 astronauts returned samples containing strange white pebbles that suggested the lunar highlands are composed of an igneous rock called anorthosite. The rock contains large amounts of a mineral class called plagioclase feldspars. These minerals, composed of sodium and calcium aluminum silicates, are commonly found in Earth's crust. The samples also contain small amounts of pyroxenes and olivine. The strangeness of this finding comes from the relative purity of the feldspars; most minerals in nature are all mixed up into rocks. But Apollo showed that much of the lunar crust is composed of anorthosite and similar rocks, with high concentrations of plagioclase feldspars. That's not what scientists would have expected.

The solution had to be something like this: Soon after its formation, the Moon may have been covered by an ocean of liquid rock that crystallized as plagioclase feldspar over its surface. Another key piece of evidence centered on the solar system's largest impact basin, the South Pole-Aitken Basin on the Moon's far side. The basin's size — more than 1,500 miles (2,400 kilometers) across — shows that huge, catastrophic collisions occurred. These two lines of evidence have led to the current thinking about where the Moon came from.

Moon and Earth formed in the same region of the solar system.

About 4.6 billion years ago, two planets floated in the space now occupied by the Earth-Moon system, according to most planetary scientists. Proto-Earth had 50 to 90 percent of its current size and mass, while the second planet — a body about the size of Mars — no longer exists.

Planetary scientists believe the smaller protoplanet struck Earth at a grazing angle. The collision sped up Earth's rotation and melted the mantles of both planets and reformed them, creating the plagioclase feldspar. Later on, the majority of the impactor's mass accreted onto Earth's surface. For a time, then, after the impact, Earth would have had Saturn-like rings.

The Saturn-like disk would be unstable, however, and the Moon likely accreted from this huge mass of particles. This scenario probably occurred in as little as a few years to as many as a few thousand years, either one a very short time span in planetary terms. This hypothesis, based on geology and orbital mechanics, offers by far the best and most logical way to understand how Earth's Moon formed. 50

18

Where do **meteorites** come from?

METEOR CRATER CHUNK. **About 50,000 years ago, an iron asteroid fragment the size of a football stadium struck the Arizona desert, producing the famous Barringer Meteor Crater. The Canyon Diablo meteorite was mostly vaporized, but scattered fragments like this one remain.** *ASTRONOMY:* DAVID J. EICHER

Every night, it's possible to see a brilliant flash make its way across the sky. Meteors are beautiful, startling, and a reminder that debris lies scattered throughout the solar system; some of it falls toward Earth. Collectors prize meteorites — particles that survive to strike Earth's surface — and value holding a piece of the distant solar system in their hands.

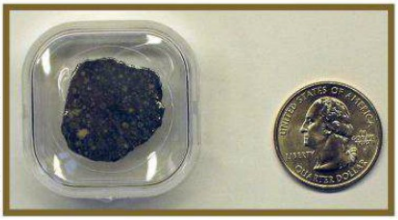
Altogether, about 24,000 meteorites have been recovered. The most common are available for a few tens of dollars for each small piece — the least common types go for several thousand dollars per gram.

Nearly all meteorites are pieces of asteroids, most of which lie in the main asteroid belt between Mars and Jupiter, but others were born in more distant reaches of the solar system. A few may be pieces of comets. Some are fragments of Mars or the Moon.

How do scientists know about the origins of meteorites? First, they separate meteorites into three classes — stones, irons, and stony-irons. In general, irons originate in the metallic cores of asteroids, while stones are pieces of the outer mantle or crust of asteroids. Stony-irons, rare compared with the others, are boundary pieces containing mostly metals but also silicate minerals.

Within the class of stone meteorites exists an important type called carbonaceous chondrites. These meteorites contain chondrules, millimeter-sized orbs of minerals that were once molten droplets. These primitive meteorites give scientists a window to the early solar system; the chondrites formed from aggregates of dust flash-melted during the solar system's earliest days, when the Sun and Earth were forming. Meteorites, like the one that fell in Allende, Mexico, or the inky-black, carbon-dominated Tagish Lake specimen from British Columbia, provide an unfettered glimpse at the most primitive matter we know about.

ANCIENT MESSENGER. **Inclusions in the Allende meteorite, which fell in Mexico in 1969, date back 4.55 billion years. This carbonaceous chondrite stone meteorite contains solidified drops of minerals from the ancient solar system.**

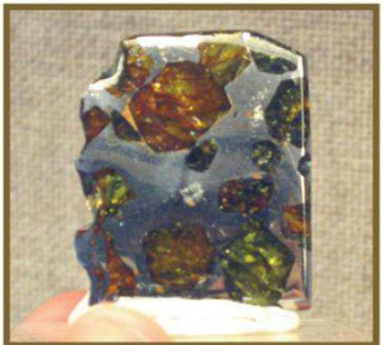


ASTRONOMY: DAVID J. EICHER

About 95 percent of meteorites that fall are stones. Of those, 34 are known to have originated from Mars. How is this possible? Take the case of the largest and most celebrated martian meteorite, Zagami, which fell in Nigeria in 1962. Zagami is a basaltic shergottite, which means it's similar to Shergotty, the second martian meteorite found. Zagami's solidified lava crystallized about 1.3 billion years ago in a magma chamber. The certainty of its martian origin comes from its young age (much younger than the crystallization ages of most meteorites), the gas isotopic composition that matches the martian atmosphere (compared to Viking lander data), and the high deuterium-to-hydrogen ratio.

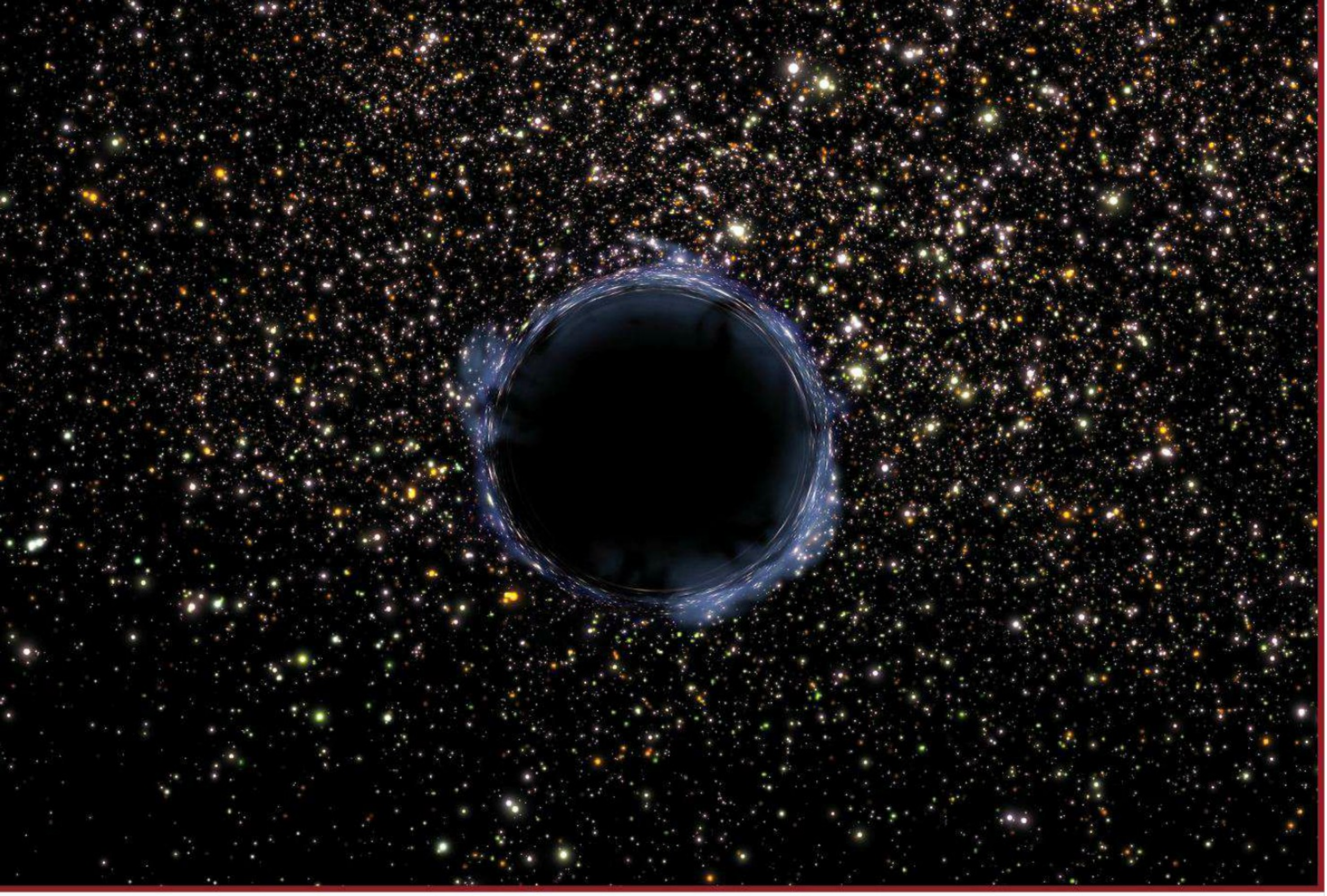
Similarly, 39 meteorites are known to have come from the Moon. As with the martian meteorites, these objects were knocked into space in antiquity by large impacts, and their orbits eventually brought them into Earth's gravitational tug. As an example, Dar al Gani 400, the largest lunar meteorite, fell in the Libyan Sahara in 1998. It is a feldspathic regolith breccia, meaning it contains large amounts of the mineral anorthite, a calcium-aluminum silicate mineral that is abundantly present in the lunar highlands. The lunar meteorites' chemical compositions, isotope ratios, mineralogies, and textures all match the samples brought back by the Apollo astronauts.

All meteorites except those from the Moon and Mars, however, originated from the asteroid belt. Because of the numerous similarities among meteorites and asteroids, their huge numbers, and the fact that many asteroids have since fragmented and broken up, it's difficult to match meteorites with their parent bodies. Three subclasses of stone meteorites — howardites, eucrites, and diogenites — are high-temperature basaltic rocks similar in composition to the asteroid 4 Vesta, so Vesta is likely their parent body. The primitive carbonaceous chondrite Tagish Lake has been spectroscopically tied to asteroid 368 Haidea. Most associations are made simply by asteroid classes, as astronomers have much more work to do to tie specific asteroids to meteorites that have fallen to Earth.



ASTRONOMY: DAVID J. EICHER

CELESTIAL ART. A rare type of meteorite — stony-iron pallasites — contains a metallic matrix included with the mineral olivine. Astronomers believe these seldom-found space rocks formed at the boundary between an asteroid's core (metallic) and mantle (stone). The most beautiful pallasite, the Esquel meteorite shown here, was found in Argentina in 1951.



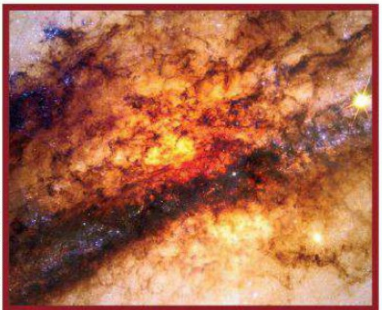
19 Can light escape from black holes?

STOP THE LEAK! If black holes are, by definition, regions from which nothing can escape, then how could light "leak" from them? Viewed in terms of quantum mechanics, black holes are not quite black: They release small amounts of light called Hawking radiation. NASA/G. BACON

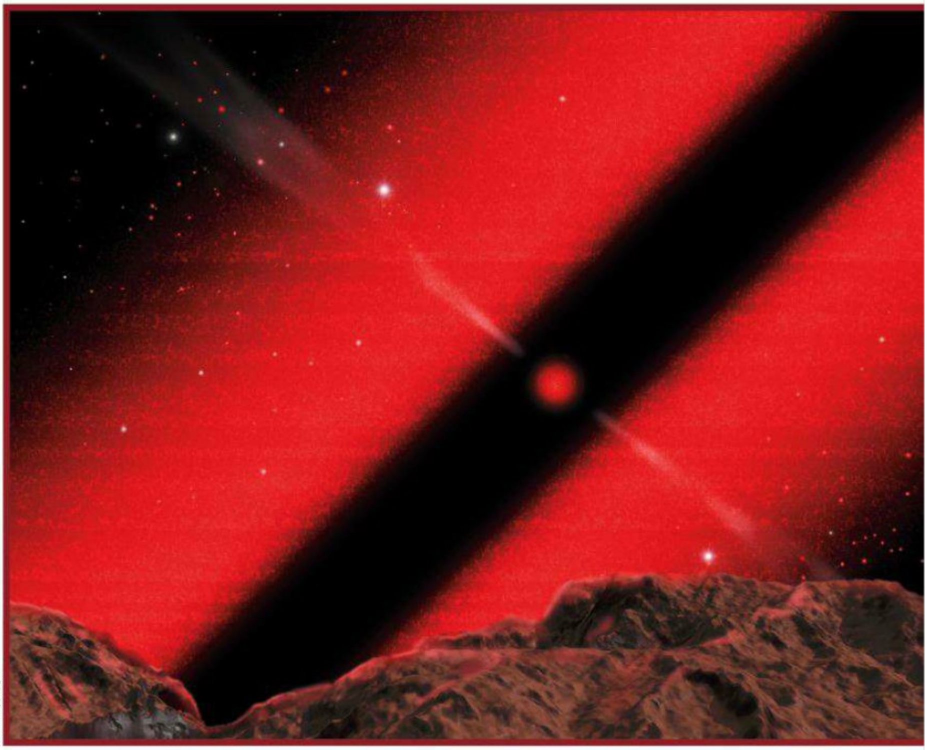
Four decades after theories predicted the existence of black holes, astrophysicists held a simple view of them. They were concentrations of mass so great that no light could escape their staggering gravitational pulls. Astronomers believed black holes are black because they are bounded by a limit called the event horizon, which traps radiation in wells out of which no electromagnetic radiation can escape.

The concept of such "dark stars" was put forward as early as 1783 by British geologist John Michell. In the 1920s and 1930s, astrophysicists tightened theories about black holes, but it wasn't until the last 25 years that astronomers began to collect good observational evidence of black holes' existence. The label held fast: Black holes were black because nothing could escape their gravitational grasps. Black holes had to be observed through their interactions with other, nearby bodies subject to their influence.

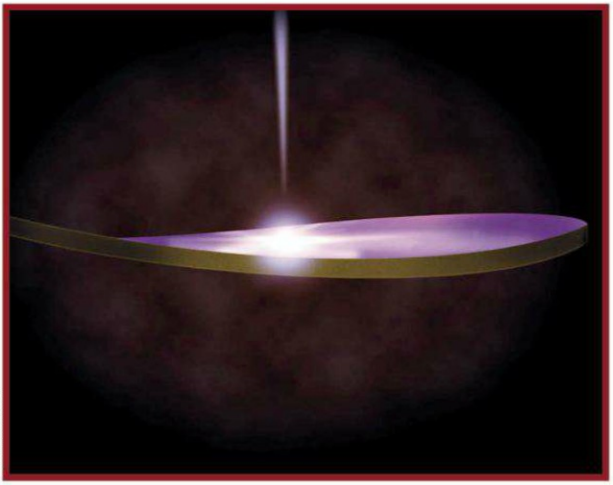
But this straightforward view of black holes began to change in 1974. In that year, British cosmologist Stephen Hawking worked out a complex set of equations about black holes using quantum field theory. To the astonishment of physicists, Hawking showed that black holes can actually emit radiation. The notion that nothing at all can escape a black hole now seemed wrong. The resulting emission, small as it may be, was dubbed Hawking radiation.


E. J. SCHREIER/STScI/NASA

REAWAKENED GIANT. In the center of this Hubble image of nearby galaxy Centaurus A, a supermassive black hole lurks and feeds on a smaller colliding galaxy. When galaxies fuel dormant black holes that lie within them, sparks fly.


J. GITLIN/STScI

▲ RED SKY RISING. The active galaxy NGC 4261 harbors a supermassive black hole. An observer on a hypothetical planet orbiting a star in this galaxy might see the night sky as shown in this illustration.


JAMES GITLIN/STScI

◀ DISK WARP. A suspected black hole in the active galaxy NGC 6251 is surrounded by a warped, dusty disk of material, shown in this illustration. Images of the real disk reveal that only one side reflects light, creating its unusual warp.

Hawking showed there are several ways to understand how energy can escape a black hole. First, separation of matter-antimatter pairs occurs just beyond the event horizon. This would produce radiation not from within the black hole itself, but from virtual particles getting boosted to higher energy states by the black hole's gravitation. Another way to look at the process is that vacuum fluctuations could cause a particle-antiparticle pair to appear close to the event horizon. One particle could fall into the black hole, while the other would not. To fill the "hole" in energy left by the lone particle, energy could tunnel its way out of the black hole and across the event horizon, producing the observed radiation. This would cause the black hole to lose mass, and an observer would see radiation being emitted from the black hole.

If black holes can lose mass, then it logically follows that at least some of them could eventually disappear. This process is called black-hole evaporation. When particles escape from a black hole, the black hole loses not only energy, but also mass, because the two are interchangeable equals, as governed by Einstein's famous $E=mc^2$ equation. For the simplest kind of a black hole, a non-charged, nonrotating Schwarzschild black hole, physicists can estimate the amount of Hawking radiation that should be produced. A one-solar-mass black hole would produce a tiny output of energy — only about 10^{-28} watts. That's pretty close to being absolutely black!

Assuming a black hole is dormant — not accumulating any more matter — it's possible to calculate how long it would take one to evaporate. For a one-solar-mass black hole, the answer is staggering: 10^{67} years, or more than a million times longer than the whole history of the universe to date. But tiny black holes would evaporate more quickly, provided they were not gorging on radiation and stars. A black hole with the mass of 10^{22} pounds (10^{11} kilograms) would disappear in only 3 billion years.

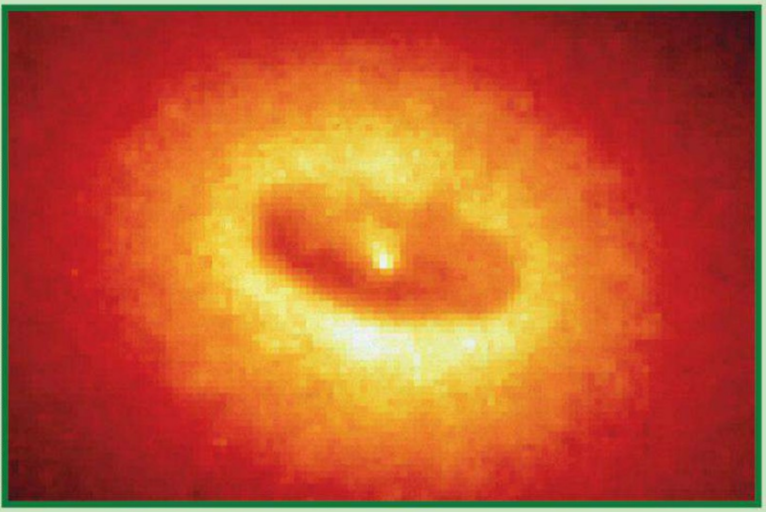
The classical concept of black holes being black is nearly right, but not exactly. Stephen Hawking showed the world that black holes can show themselves, although the evidence may be subtle, and that — given enough time — they can even vanish.

20

Did **stars, galaxies,** or **black holes** come first?

Although astronomers understand certain aspects of the universe clearly, others are more muddled. The Big Bang has a mountain of evidence behind it, while the picture of how protogalaxies evolved into normal galaxies in the first few billion years of the cosmos is just coming together. But what happened, exactly, at the end of the cosmic Dark Ages, following the Big Bang, that brought together the seeds of matter to form the first stars and galaxies? That question is still wrapped in a hazy cloud of mostly speculation.

At the core of the issue is which came first: stars, galaxies, or black holes? With respect to galaxy formation, many astronomers believe in the "bottom-up" model of how matter came together. In this model, small clumps merged repeatedly to form protogalaxies, and further, that many small protogalaxies clumped together to form the larger, normal galaxies we see in the nearby universe today (see "How did the Milky Way Galaxy form?" p. 75). But others believe giant sheets of matter formed in galaxy superclusters and then broke apart into smaller units. Either way, no one yet knows whether the gas and dust that came together to make galaxies preceded star formation or whether stars formed simultaneously as the first units of matter fell together to form the earliest protogalaxies.



NASA/WALTER JAFFE (LEIDEN OBSERVATORY)/HOLLAND FORD (JHU/STScI)

BLACK HOLE CANDIDATE. Elliptical galaxy NGC 4261 may contain a black hole at its core. The Hubble Space Telescope snapped this image of a giant disk of cold gas and dust surrounding, and possibly fueling, what is likely a black hole.

A more intriguing question arises from observations of numerous quasars in the early universe. Quasars are the energetic "central engines" found in infant galaxies that spew vast amounts of high-energy radiation into space. They are the second most energetic things in the universe (following the Big Bang) after certain gamma-ray bursts. Matter spiraling into black holes at high velocities creates quasar emissions. By observing quasars in so many galaxies in the early universe, astronomers have come to believe quasars existed in virtually every galaxy near the beginning, save for tiny ones not massive enough to support a central black hole. So an intriguing question has come about: Did galaxies form and develop black holes in their centers, or did black holes form first and act as the gravitational "seeds" that attracted matter to form galaxies?

> Black holes start forming before galaxies do, or form at a much faster rate, or both.

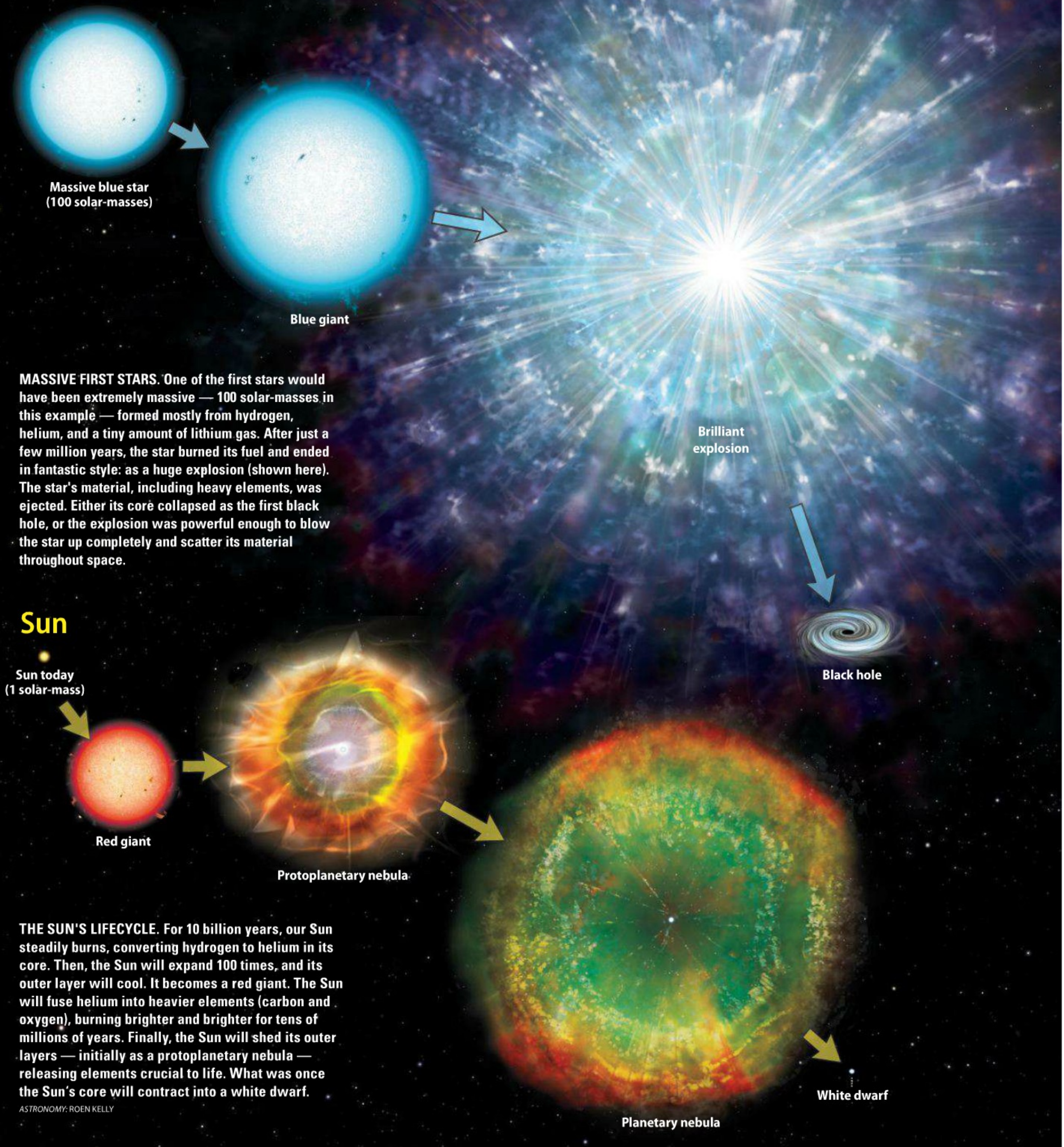
The jury is still out on this question. However, astronomers have conducted some research that may provide clues. In 2003, Marianne Vestergaard, then a postdoctoral fellow at Ohio State University, suggested black holes form first as galaxy seeds.

Vestergaard studied a collection of quasars about 12 billion light-years distant. Rather than postulating that black holes form after matter builds up in the centers of galaxies, she "think[s] that black holes start forming before galaxies do, or form at a much faster rate, or both."

The evidence came from studying a set of quasars from Sloan Digital Sky Survey data and comparing their spectra to those of quasars that are closer to Earth. After looking at several hundred quasars, Vestergaard noticed a pattern: Even the smallest, most inactive galaxies studied have supermassive black holes at their centers.

Presumably, those black holes should have taken a considerable amount of time to grow to their current sizes. However, the galaxies surrounding them showed signs of youthful vigor. This suggests the black holes may have come first.

The first stars and their descendants


Massive blue star
(100 solar-masses)
Blue giant
Brilliant explosion
Black hole
Sun today
(1 solar-mass)
Red giant
Protoplanetary nebula
Planetary nebula
White dwarf

First star

MASSIVE FIRST STARS. One of the first stars would have been extremely massive — 100 solar-masses in this example — formed mostly from hydrogen, helium, and a tiny amount of lithium gas. After just a few million years, the star burned its fuel and ended in fantastic style: as a huge explosion (shown here). The star's material, including heavy elements, was ejected. Either its core collapsed as the first black hole, or the explosion was powerful enough to blow the star up completely and scatter its material throughout space.

Sun

THE SUN'S LIFECYCLE. For 10 billion years, our Sun steadily burns, converting hydrogen to helium in its core. Then, the Sun will expand 100 times, and its outer layer will cool. It becomes a red giant. The Sun will fuse helium into heavier elements (carbon and oxygen), burning brighter and brighter for tens of millions of years. Finally, the Sun will shed its outer layers — initially as a protoplanetary nebula — releasing elements crucial to life. What was once the Sun's core will contract into a white dwarf.

ASTRONOMY: ROEN KELLY

COSMIC-RAY GUN. Supernovae — exploding massive stars — are one important source of cosmic rays. Astronomers combined images made with the Hubble Space Telescope (red) and Chandra X-ray Observatory (blue) to create this portrait of the Crab Nebula (M1) in Taurus.

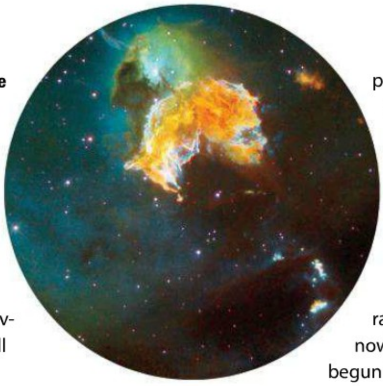
NASA/ASU/J. HESTER ET AL.

21

Where do **cosmic rays** come from?

After the discovery of radiation by French physicist Henri Becquerel (1852–1908) in 1896, scientists believed atmospheric ionization (where an electron is stripped from an air molecule) occurred only from radioactive elements found in ground rocks or from radioactive gases. Austrian physicist Victor Hess (1883–1964) found an additional source in 1912, when he strapped three electrometers into a balloon and measured atmospheric radiation at an altitude of about 15,000 feet (4,600 meters).

He found an ionization rate about 4 times greater than at ground level. Hess could explain the variant observations only if a powerful source of radiation were penetrating the atmosphere from above. Much later, in 1936, Hess received the Nobel Prize



HEAVY BOOM. **A massive supernova remnant, N63A, marks the site of a blast of cosmic rays that occurred when a star 50 times more massive than the Sun ended its life.** NASA/ESA/HEIC/THE HUBBLE HERITAGE TEAM

in physics for the discovery of what we now call cosmic rays.

Physicists initially believed cosmic rays were gamma rays, high-energy radiation produced by radioactive decay. During the 1930s, however, experiments revealed that cosmic rays are mostly charged particles. In 1937, French physicist Pierre Auger (1899–1993) found that extensive particle showers (called air showers) occur when cosmic rays collide with particles high in the atmosphere, producing a cascade of electrons, photons, and muons (particles similar to electrons but 200 times as massive) that reach Earth's surface.

In 1954, members of the Rossi Cosmic X-ray Group at the Massachusetts Institute of Technology in Cambridge made the first samplings of extensive air showers. The network of detectors at Harvard College Observatory produced much data on cosmic rays and their levels of energy.

In Argentina, the Pierre Auger Observatory opened in 2003 and aims to detect extremely high-energy cosmic rays. This international project will include a northern component in southeastern Colorado. The particles under detection have as much energy as a tennis ball traveling at 340 mph (550 km/h), packed into the space of a single proton. Physicists have nicknamed them "Oh-my-God particles."

Aside from the Auger Observatory, other cosmic-ray research projects include HiRes at the University of Utah; MARIACHI, a project of the National Science Foundation, Stony Brook University, and Brookhaven National Laboratory; and SLAC, at the Stanford Linear Accelerator.

When the particles produced in air showers decay, three kinds of neutrinos result. Because neutrinos so rarely interact with other matter, most pass through Earth undetected. But ambitious detector projects now in operation are searching for neutrinos produced by cosmic-ray showers. In 1998, the Super-Kamiokande detector in Japan found evidence of one type of neutrino changing into another "flavor."

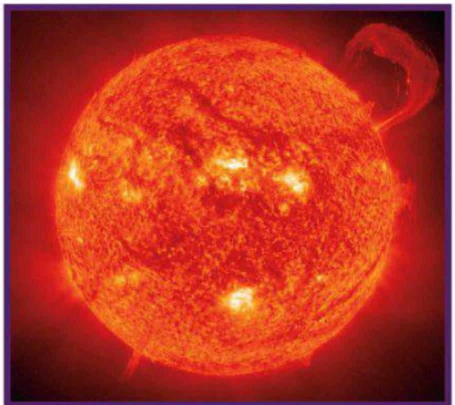
By studying cosmic rays for several decades now, astronomers have begun to understand them.

Astronomers categorize cosmic rays into four basic types. The first are those with low energies, called anomalous cosmic rays. They probably originate in the heliosheath, at the solar system's edge, where the solar wind no longer has any effect. Astronomers believe anomalous cosmic rays occur when electrically neutral atoms in the heliosheath are ionized and accelerated. However, when the Voyager 1 spacecraft passed into the inner edge of the heliosheath, it did not detect any such particle acceleration. So the jury is still out.

The second type, galactic cosmic rays, flows into the solar system from other parts of the Milky Way. Astronomers believe supernovae produce most cosmic rays of this type. In the aftermath of a supernova explosion, particles bounce repeatedly within the gaseous remnant and accelerate into cosmic rays. At some critical point, they escape into the galaxy.

Third are the abundant cosmic rays that originate from the Sun. Most of these are protons, particles at relatively low energies. The intense magnetic fields at the Sun's surface energize them.

The last kind are ultrahigh-energy cosmic rays, the type being sought by the Auger Observatory and other projects. These include the Oh-my-God particles. Scientists don't yet know these particles' origins, although researchers plan a number of experiments to try to understand them.



SOHO

LOCAL STREAM. The Sun produces a stream of cosmic rays that constantly bombards our planet. This Extreme Ultraviolet Imaging Telescope photo, made with the SOHO spacecraft February 17, 2001, shows a huge loop prominence at upper right.

NASA/ESA/THE HUBBLE HERITAGE TEAM

DARK AND MURKY. **The interstellar medium, gas and dust between the stars, produces cosmic rays that reach Earth. A pillar of gas and dust in the Eagle Nebula (M16) reveals the rich structure of the stuff that fills our galaxy.**

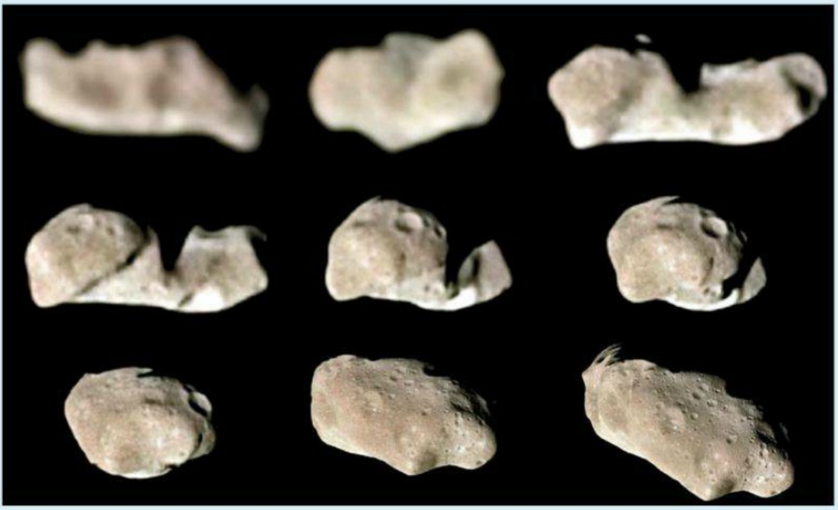
22

How are **comets** and **asteroids** related?

The solar system is a complex place. Aside from the Sun and major planets, it is filled with hundreds of thousands of smaller bits of debris left from the solar system's formation, some 4.6 billion years ago. In the 19th century, astronomers were concerned primarily with discovery. Whether moons, comets, or asteroids, finding and cataloging objects was the primary means of employment. And it is still an important part of the scientific process, because many unusual and important objects certainly remain to be found.

But in recent times, planetary scientists have turned increasingly to interpreting what they have found. Analyzing objects by an increasing number of techniques has allowed astronomers to paint a sharper picture of the solar system's formation and the relationships between objects in it.

For many years, astronomers kept comets and minor planets, or asteroids, in separate categories. After all, comets are frozen balls of ice and gas that live in the solar system's distant reaches. Occasionally, through a gravitational kick, they travel inward, heating up and putting on a show with their spectacular tails.



NASA/JPL

SPACE SPUD. **This set of nine color images of the asteroid 243 Ida reveals the potato-shaped structure of this space rock, which measures 36 by 14 miles in extent. The image was recorded by the Galileo spacecraft August 28, 1993.**

Asteroids, on the other hand, are rocky bodies — micro-planets, if you will — most of which reside in the asteroid belt, which lies between Mars and Jupiter. Asteroids show no traits similar to comets, such as the outgassing of volatiles that form pretty tails in the sky. Moreover, their orbits are distinctly different from those of comets.

But a view developed during the past 15 years suggests comets and asteroids, although distinct types of bodies, are more alike than astronomers originally thought. Trillions of comets probably exist in our solar system; the long-period ones exist in a vast reservoir called the Oort Cloud, named after Dutch astronomer Jan Oort (1900–1992), who hypothesized its existence.

Periodically, a gravitational kick from a passing star or a disturbance in the Oort Cloud sends long-period comets inward toward the Sun. Short-period comets, on the other hand, reside closer in and have orbits with periods less than 200 years.

NASA/JPL-CALTECH/UMD

WHAMMO! **Comet 9P/Tempel 1 dances with light moments after the Deep Impact spacecraft impactor's strike into the nucleus July 4, 2005. Comets and asteroids are both leftover debris from the primordial solar nebula, some 4.6 billion years ago.**

Comets with hyperbolic or parabolic orbits appear only once, after which they are flung outside the solar system. Lastly, main-belt comets, a group consisting of only three members, reside in the main asteroid belt. Similar objects, with their circular orbits, may have deposited water on Earth billions of years ago. This class, now consisting of 133P/Elst-Pizarro, 118401 1999 RE_{70}, and P/2005 U1, exists at the crossroads between comets and asteroids.

By contrast, scientists know of 330,000 minor planets. Of these, more than 129,000 have been studied well enough to warrant permanent numerical designations, and more than 13,000 asteroids have names. Astronomers believe the total number of asteroids in the solar system larger than 1 mile (1.6 km) across is about 1 million.

The largest asteroid in the main belt is Ceres, which has a diameter of about 600 miles (970 km). Altogether, the mass of main-belt asteroids adds up to only about 4 percent of the Moon's mass.

NASA/NOAO/NSF/T. RECTOR, Z. LEVAY, AND L. FRATTARE

During the 1980s and 90s, scientists' neat distinction between comets and asteroids began to blur. With the discovery of the Kuiper Belt (see "How many asteroids are locked up in the Kuiper Belt?" p. 50), it became clear that a vast population of icy bodies existed on the solar system's fringe, much closer than the Oort Cloud.

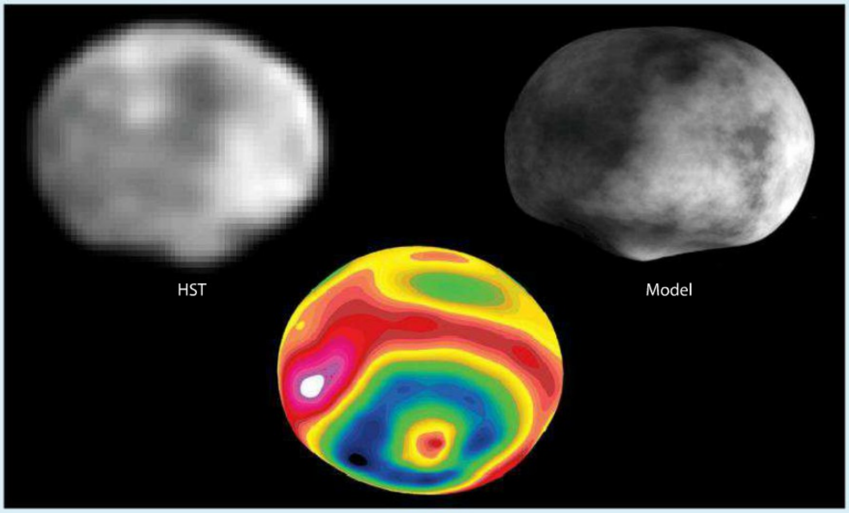
Discoveries of main-belt comets further blurred the distinction. Certainly, some main-belt asteroids could be ancient ex-comets whose volatiles evaporated long ago, leaving a rocky core.

The discoveries of other bodies with peculiar properties led to the cross-listing of several objects as both asteroids and comets. These include 2060 Chiron, an object discovered in 1977 by American astronomer Charles T. Kowal, then at Palomar Observatory. It's the first member of an asteroid class known as centaurs, with orbits between Saturn and Uranus. This unusual asteroid came under intense study, and, in 1988, astronomers watched it surprisingly undergo an outburst in brightness, an act characteristic of comets, not asteroids.

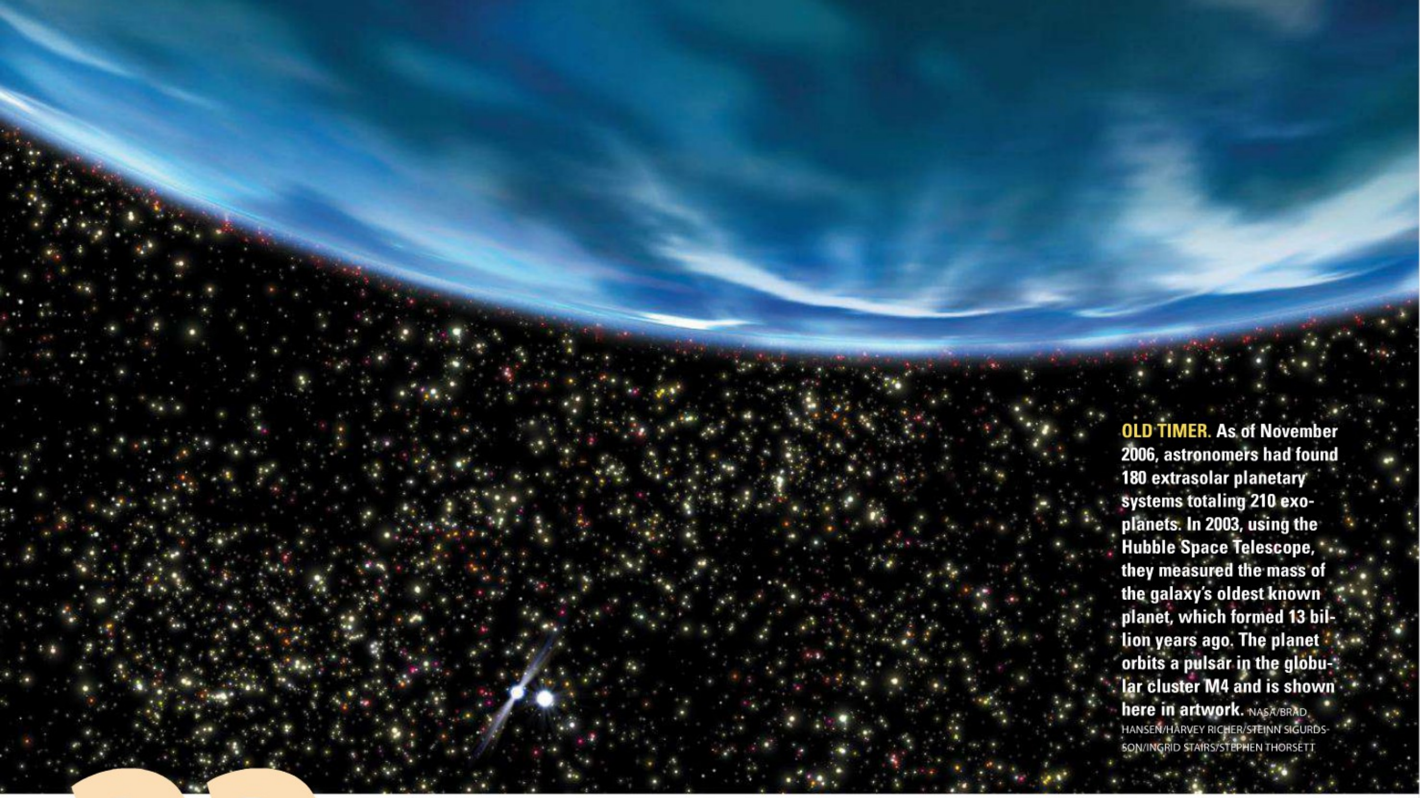
Additionally, 60558 Echeclus, a centaur discovered in 2000, appeared to be an innocent asteroid. In late 2005, astronomers found a faint cometary coma surrounding this body. Finally, 4015 Wilson-Harrington, an object first observed as a comet in 1949 and later independently discovered as an asteroid in 1979, shares both designations. The 1949 observations showed cometary characteristics, while the later ones did not. All this points to a complex solar system in which the orbits and behaviors of asteroids and comets are related more than astronomers originally envisioned. ▪

▲ DIRTY ICEBALL. Comet C/2001 Q4 NEAT typifies the kind of soft coma and glowing tail that amateur astronomers hope to see through their telescopes. Astronomers using the WIYN Telescope on Kitt Peak, Arizona, caught this view of NEAT May 7, 2004.

▼ HOLY ASTEROID. In 1997, astronomers using the Hubble Space Telescope discovered a huge impact crater on the asteroid 4 Vesta. The crater spans 285 miles, a significant portion of Vesta's 325-mile diameter. The image at left shows an HST view; at center, a color-coded version clearly reveals the crater's contours; and at right, a 3-D computer model shows Vesta's surface.



BEN ZELLNER/PETER THOMAS/NASA



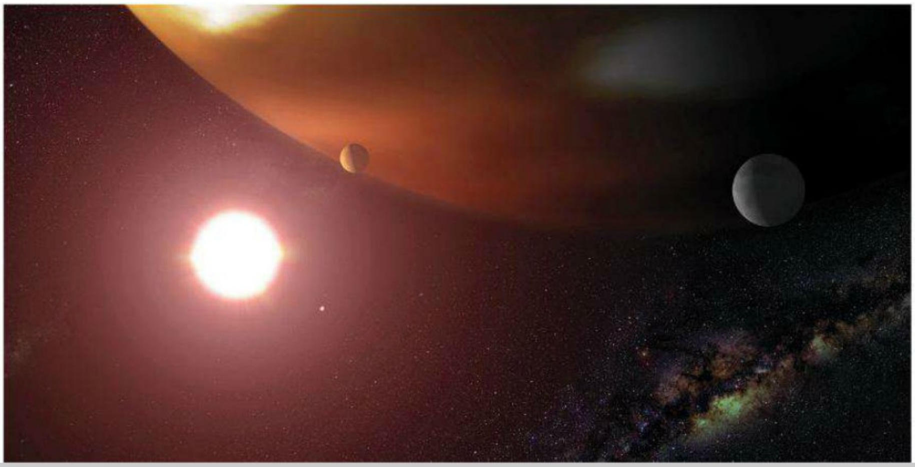
OLD TIMER. **As of November 2006, astronomers had found 180 extrasolar planetary systems totaling 210 exoplanets. In 2003, using the Hubble Space Telescope, they measured the mass of the galaxy's oldest known planet, which formed 13 billion years ago. The planet orbits a pulsar in the globular cluster M4 and is shown here in artwork.** NASA/BRAD HANSEN/HARVEY RICHER/STEINN SIGURDSSON/INGRID STAIRS/STEPHEN THORSETT

23

How many **planets** surround other **star systems**?

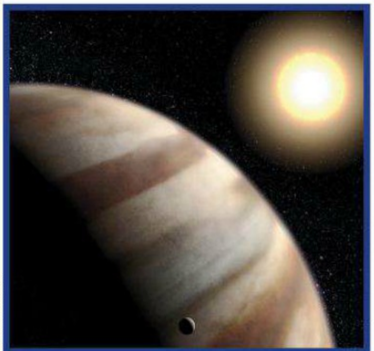
Standing under a dark night sky, looking out at the Milky Way, it's hard to imagine countless planets don't exist elsewhere in the universe. After all, some 200 to 400 billion stars inhabit our galaxy, and astronomers estimate at least 125 billion other galaxies exist. That's one heck of a number of stars in the universe — at least 25,000 billion billion. Looking at the nebular hypothesis, which describes how the solar system formed (see "How did the solar system form?" p. 77), it seems clear most stars would form planets as their protogenitor clouds collapsed. Yet, due to the immense distances, seeing other planetary systems remained a supreme challenge for astronomers until the past decade.

The first suspected detections of extrasolar planets, or exoplanets, as they are called, occurred in 1989. That year, astronomers reported variations in the radial velocities of two stars — HD 114762 in Coma Berenices and Alrai (Gamma Cephei) — and attributed those observations to the pull of exoplanets.



MINI JOVE. **In 2002, astronomers measured the mass of Gliese 876b, an exoplanet orbiting a red dwarf star 15 light-years away in the constellation Aquarius. They found the little planet, depicted here in artwork, has only half Jupiter's mass.**

NASA/G. BACON


G. BACON/STScI

LONG-RANGE WEATHER. In 2001, astronomers measured an atmosphere around an exoplanet. In this artwork, the planet appears as a Jupiter-like world only 4 million miles from its star.

However, follow-up data showed the cause was unknown, and it took another 10 years to confirm exoplanets orbit these stars. Meanwhile, in 1992, another astronomer claimed to detect an exoplanet orbiting the pulsar PSR 1257+12. Astronomers eventually confirmed this "pulsar planet," as it came to be known.

During the mid-1990s, exoplanet detection boomed. Astronomers honed their techniques and created improved instruments, and, by 1995, they observed the first exoplanet around a Sun-like star. The first discovery of an exoplanet was around the star 51 Pegasi. By November 2006, astronomers had discovered 210 planets in 180 separate Sun-like systems. Additionally, four exoplanets are known to orbit two pulsars.

Detecting exoplanets is tricky because the feeble light from the planets appears next to the bright glare of the host stars. At present, astronomers use six techniques to find exoplanets. The first is pulsar timing, the method used to find the planet orbiting PSR 1257+12. This technique measures anomalies in the regularity of the pulsar's pulses.

Second, astronomers have employed astrometry, precise positional measurements, to attempt exoplanet detection since 1943. However, it has failed to uncover an extrasolar planet.

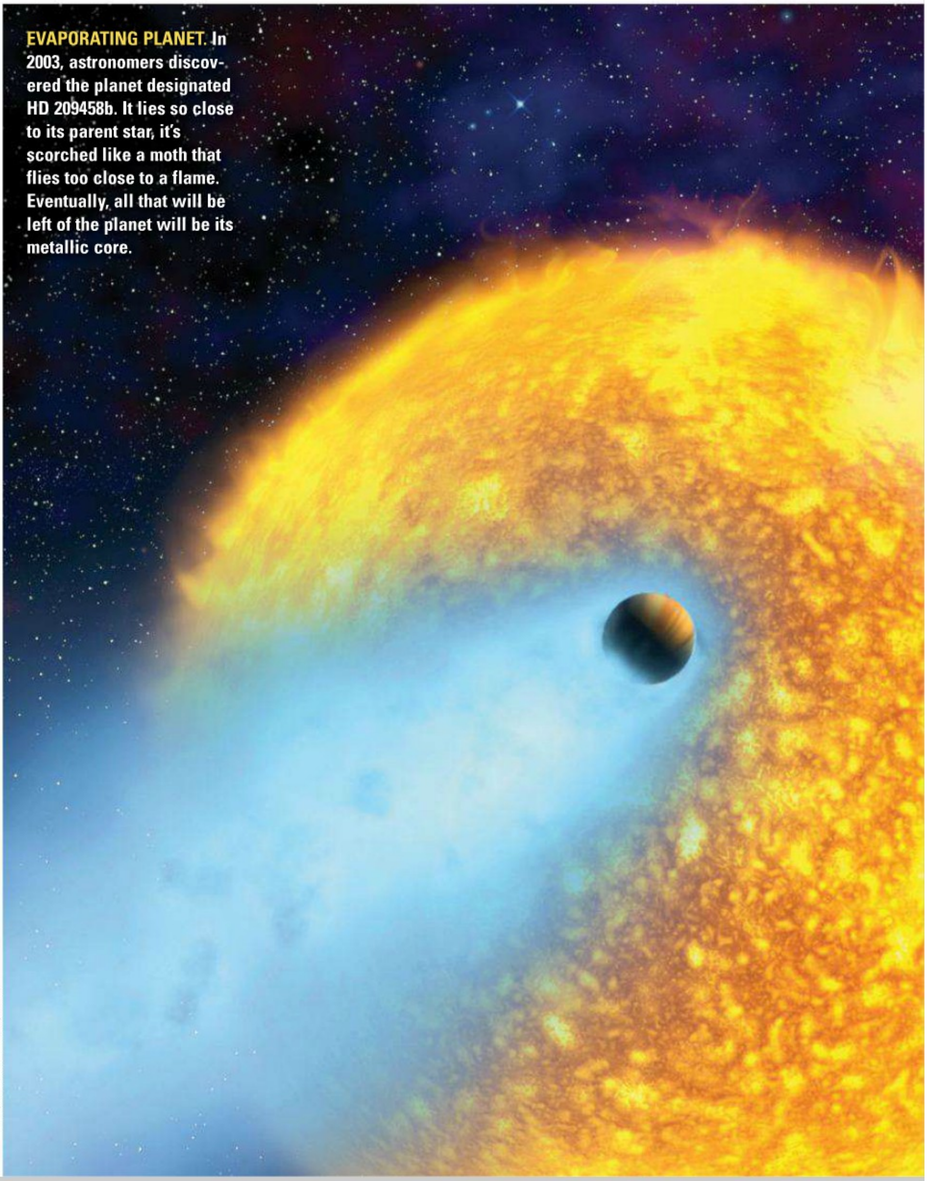
Third is the radial velocity method, which measures the speed at which an object (in this case, a star) moves toward or away from Earth. An exoplanet's gravitational tug creates anomalies in the star's speed. This is by far the most successful method astronomers now use in the exoplanet hunt, resulting in most of the finds thus far.

The fourth technique is called gravitational microlensing, in which the gravitational field of a star and its exoplanet bend the light from a distant background object. A lone star bends light differently than one with a planet orbiting it. The number of background stars seen with this technique is maximized when astronomers look at stars between Earth and the galactic center.

Fifth is the transit method. Through this technique, astronomers detect exoplanets as they pass in front of their host star, causing a drop in light intensity.

The final method, direct observation, first worked in 2005, when astronomers used the Spitzer Space Telescope to image infrared radiation from two exoplanets.

With the number of exoplanets growing week by week, researchers plan new and ambitious projects to expand the number of discoveries dramatically. The exoplanets found thus far are nearly all large "hot Jupiters." Future missions such as COROT, Darwin, and Kepler will attempt to find smaller, rocky, earthlike planets that must inhabit the galaxy in vast numbers.


EVAPORATING PLANET. In 2003, astronomers discovered the planet designated HD 209458b. It lies so close to its parent star, it's scorched like a moth that flies too close to a flame. Eventually, all that will be left of the planet will be its metallic core.

ESA/A. VIDAL-MADJAR/NASA

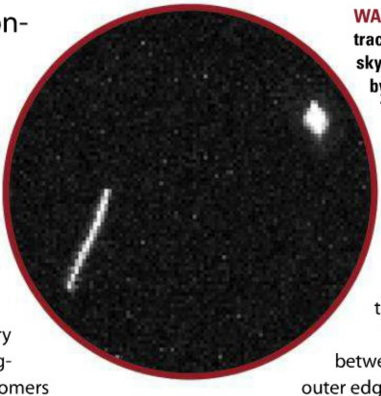
24

How many **asteroids** are locked up in the **Kuiper Belt**?

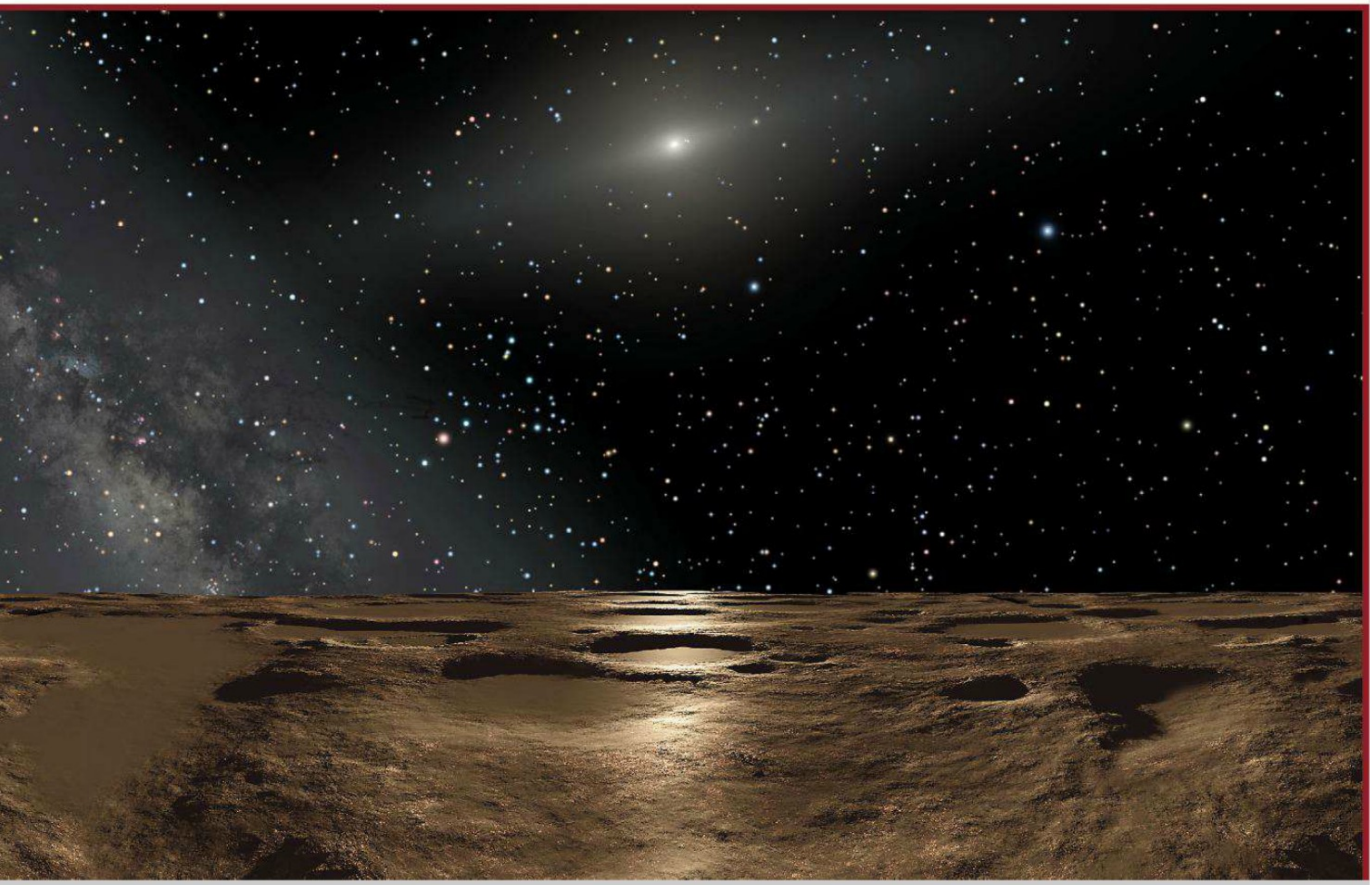
In 1930, American astronomer Frederick C. Leonard proposed the existence of a band of small bodies in the solar system that extends from Neptune's orbit to a diameter of about 50 astronomical units (AU). Leonard based this hypothesis on models of solar-system formation and on orbital dynamics of the outer planets. Nearly a decade later, Dutch-American astronomer Gerard Kuiper (1905–1973) published research on the proposed belt and suggested it was the source of many short-period comets. During the 1960s, 1970s, and 1980s, researchers searched for Leonard's outer solar system belt but found nothing.

All that changed in 1992. With the discovery of asteroid 15760, designated 1992 QB$_1$, astronomers finally found a trans-neptunian object (TNO), the first real member of the hypothetical belt. Astronomers believed many other such objects lay in the region, and they named it the Edgeworth-Kuiper Belt, or alternatively, the Kuiper Belt.

The belt exists between about 30 AU, the outer edge of Neptune's orbit, and 50 AU, where Neptune's orbital resonance causes the number of objects to drop off rapidly. Farther out from the Kuiper

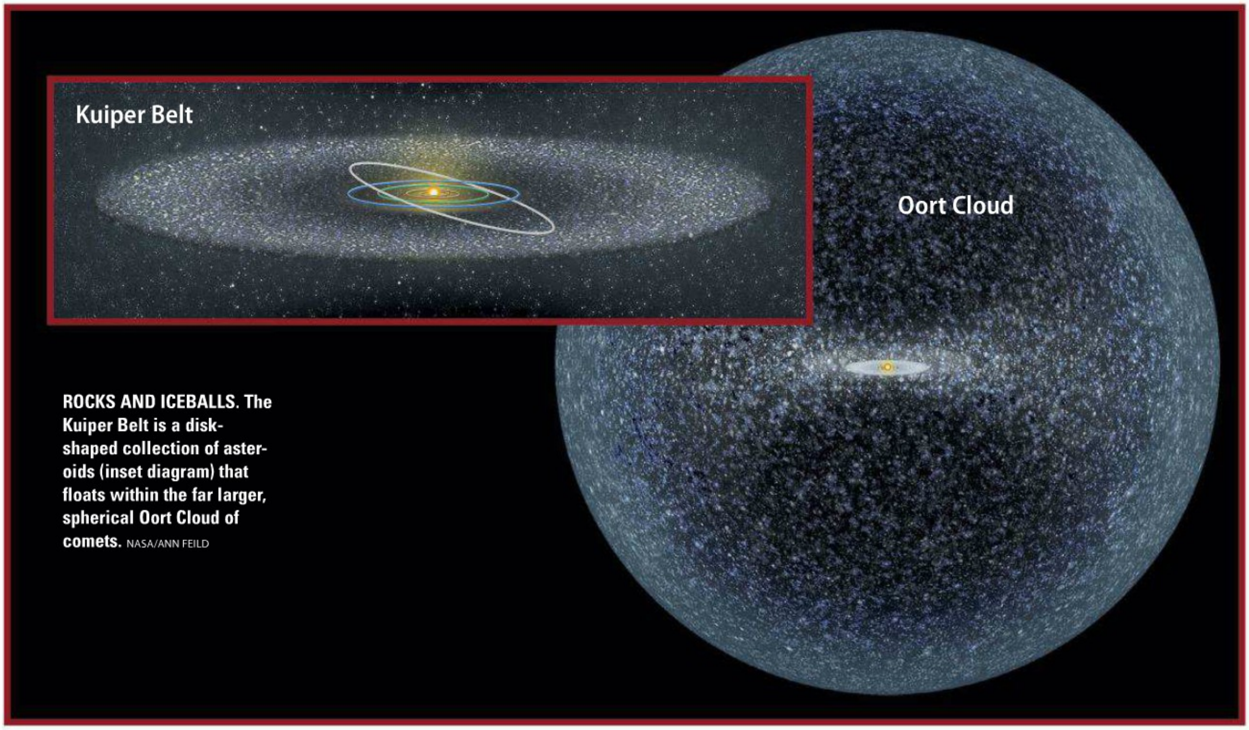


WANDERING ROCK. **Sedna tracks its way across the sky in an image captured by the Hubble Space Telescope March 16, 2004.** NASA/ESA/MIKE BROWN



DISTANT SUN. **An artist's impression of noontime on Sedna, the most distant minor planet from the Sun, shows distant, feeble rays from our star. Sedna's body temperature is –400° F on this airless, frozen world.**

NASA/ESA/ADOLF SCHALLER



ROCKS AND ICEBALLS. The Kuiper Belt is a disk-shaped collection of asteroids (inset diagram) that floats within the far larger, spherical Oort Cloud of comets. NASA/ANN FEILD

Belt are the so-called Scattered Disk and the Oort Cloud.

Over the past 14 years, the number of Kuiper Belt objects (KBOs) found has grown to more than 800. Among the noteworthy KBOs are Pluto and its largest moon, Charon, which led to the debate over whether Pluto should be classified as a planet or an asteroid (see "Should Pluto be considered a planet?" p. 64.

At least 70,000 TNOs exist with diameters larger than 60 miles (100 km).

Objects in the Kuiper Belt that have a 3:2 orbital resonance with Neptune (that is, whose orbital period measures 50 percent longer than Neptune's), like Pluto, are called plutinos. The first plutino discovered (after Pluto itself) was 1993 RO. The largest known plutino, 90482 Orcus, was found in 2004. Based on Orcus' absolute magnitude and assuming a standard reflectivity, this body likely measures 1,000 miles (1,600 km) across, as opposed to Pluto's diameter of 1,400 miles (2,250 km).

Astronomers call KBOs without the 3:2 neptunian orbital resonance cubewanos after 1992 QB$_1$ (Q – B – 1 – ohs).

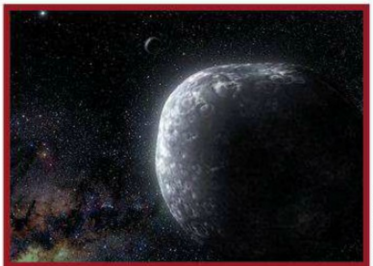
Among the most notable cubewanos is 20000 Varuna, discovered in 2000.

Another, larger discovery occurred in 2002 — 50000 Quaoar. At the time of its discovery, Quaoar, at 780 miles (1,260 km) across, was the largest object found in the solar system since Pluto, in 1930. Other significant KBOs include 2003 EL$_{61}$, which has two moons and high reflectivity due to surface ice.

Major objects found in the Scattered Disk include 1996 TL$_{66}$ (the first object cataloged as a Scattered Disk object) and Eris, formerly nicknamed Xena. This object is the largest known TNO, measuring some 1,500 miles (2,400 km) across. Another important asteroid discovery on the fringe of the solar system, that of 90377 Sedna in 2003, uncovered what is perhaps an inner Oort Cloud object that spans anywhere from 800 to 1,100 miles (1,300 to 1,800 km) across.

Although KBO numbers continue to grow, astronomers don't know the grand total of icy bodies that inhabit the Kuiper Belt. American astronomer David Jewett, codiscoverer of the first TNO, believes at least 70,000 TNOs exist with diameters larger than 60 miles (100 km) and with orbits as close as 50 AU from the Sun.

This vast reservoir of iceballs will keep astronomers busy with discoveries and cataloging for years to come. It also will allow planetary scientists to glean a clearer picture of how the solar system formed and how its outer reaches work today. ▪


NASA/G. BACON

TWO FOR ONE. The distant Kuiper Belt asteroid 1998 WW31 appears as a pair of icy bodies on the fringe of the solar system in this artwork. This binary asteroid orbits the Sun every 301 years.

25
Does **string theory** control the **universe**?

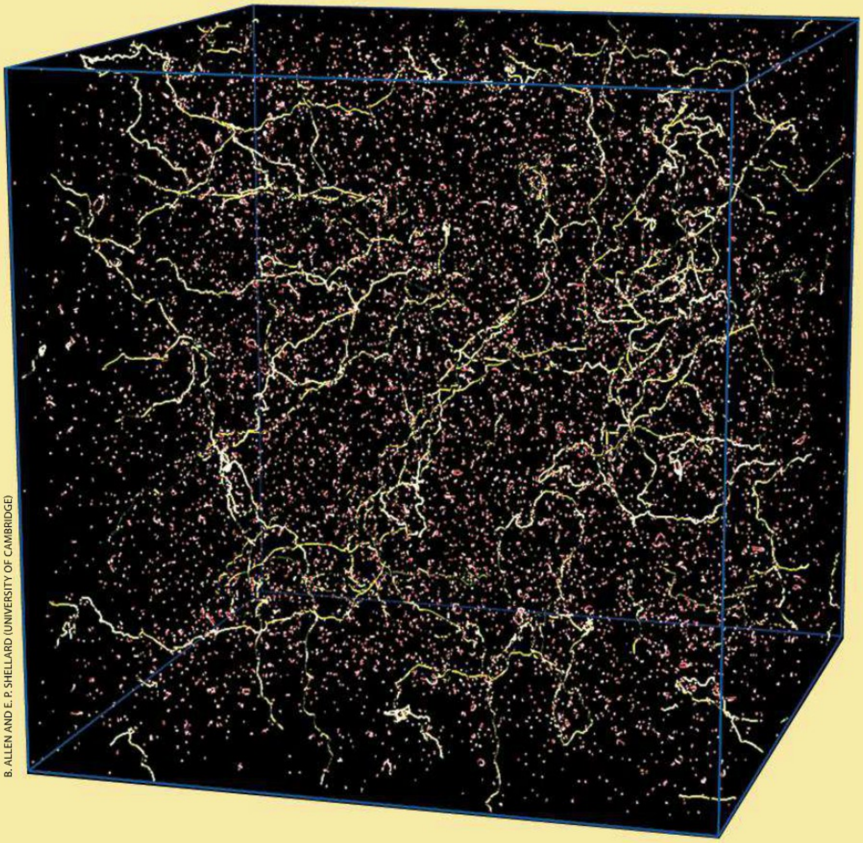
One of the strangest ideas about the nature of the universe could be one of the most important. Do long, thin, and incredibly dense strands of matter called cosmic strings wind their way throughout the universe? This theoretical idea took off with a bang in the 1980s, received a torrent of skepticism in the 1990s, and now is undergoing a resurgence of credibility.

One of the universe's strangest conundrums is the smoothness of the early cosmos following the Big Bang and how clumpy things like galaxies could have formed suddenly from it. The answer could be cosmic strings.

Cosmologists are embracing the possibilities. Edward Witten of Princeton University, one of the world's foremost theoretical physicists, says, "Strings of different sizes and kinds probably exist." Twenty years ago, Witten opposed string theory. He now believes these tiny, string-like loops of energy could be the universe's basic form of matter and energy and that some strings could reach enormous sizes.

The current incarnation of the theory suggests cosmic strings arose after the inflationary period. The strings researchers currently propose are less massive and more stable than the ones originally thought up in the 1980s. Because of these changes, they would have less effect on the cosmos than astronomers originally thought, so they would not necessarily be ruled in or out of existence by recent observations.

With the reformulation of what astronomers think strings might be, the question of whether they can be detected still hangs

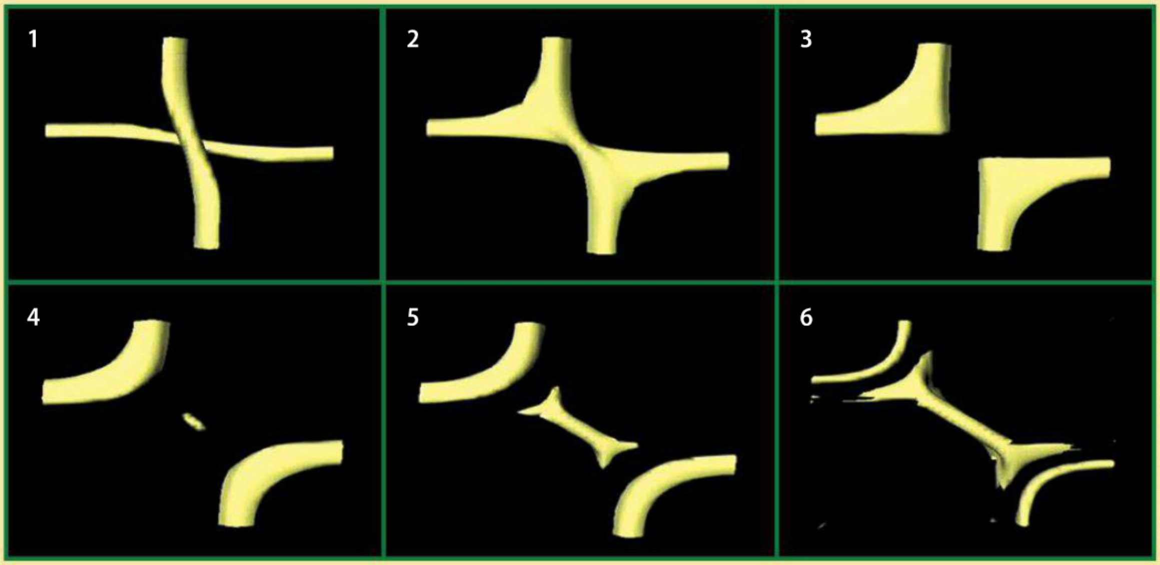


STRINGY MESS. When cosmologists model cosmic-string evolution, their goal is to predict how string properties such as speed and separation change over time. This simulation shows cosmic strings when the universe was young and dominated by radiation.

B. ALLEN AND E. P. SHELLARD (UNIVERSITY OF CAMBRIDGE)

LIKE CRACKED ICE. Cosmic strings may have formed as defects in space-time when the universe cooled. The process is analogous to cracks that form as water freezes to ice.

ASTRONOMY: JAY SMITH



R. BATTYE AND E. P. SHELLARD (UNIVERSITY OF CAMBRIDGE)

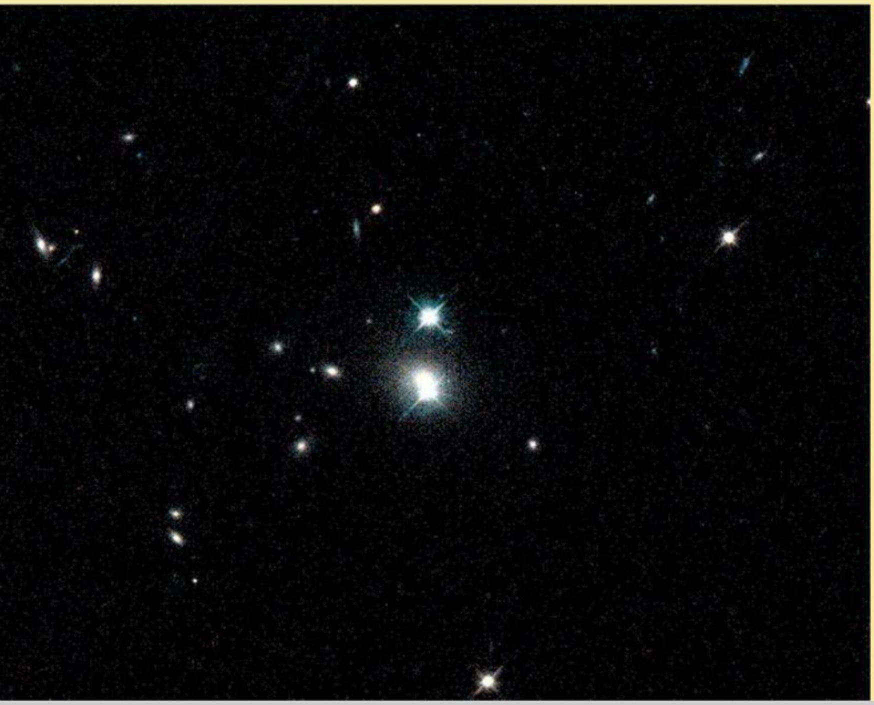
COSMIC BONES. When strings collide, they can exchange pieces and form a free-floating loop. In this computer simulation, two strings approach one another at half the speed of light. Both strings emit radiation — usually gravitational waves. A new loop forms in the collision's aftermath.

out there. Two research teams have reported evidence of cosmic strings in different parts of the sky, but these observations are unconfirmed. According to Alexander Vilenkin of Tufts University, however, who pioneered cosmic string theory by suggesting strings could have triggered the formation of galaxies, the discoveries have "breathed new life into this field."

The current thinking on cosmic strings goes as follows: When inflation occurred, "cracks" in the universe's phase transition arose, and these cracks created thin, superdense strings of matter and energy. These features might have formed like fissures in ice, along faults between transition zones. These sinewy filaments of matter might forever be frozen in a primordial state, having avoided the cosmic inflation the rest of the universe experienced.

If they exist, cosmic strings are almost unimaginably thin, yet they possess nearly unlimited length. Strings also may be incredibly dense, much denser than the matter at a neutron star's center. With such density, cosmic strings would act as gravitational lenses if they floated in front of bright background objects, and this could be one way to find one. Yet, spotting a long cosmic string could be incredibly difficult: Computer simulations suggest they would be spaced about 325 million light-years apart. The nearest long cosmic string might be 10,000 light-years away.

The possibility of detecting a cosmic string by lensing exists. Astronomers will be looking for such events with the Laser Interferometer Gravitational Wave Observatories (LIGO) and, in the next decade, with the Laser Interferometer Space Antenna (LISA). "Cosmic strings might actually provide the best observational window into fundamental string theory," says Thomas Kibble of Imperial College in London. With a rebirth of study and credibility, cosmic strings will carry on as a hot topic. ■



DEEP MIRAGE. Lensed quasars may reveal the presence of cosmic strings.

NOAO/AURA/NSF

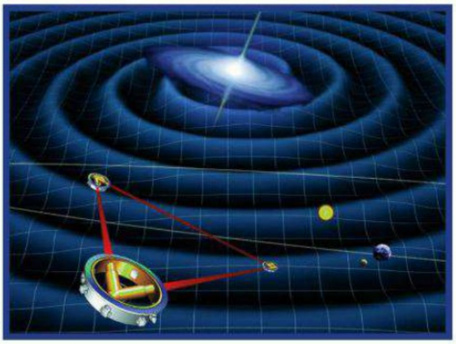
26

What creates gravitational waves?

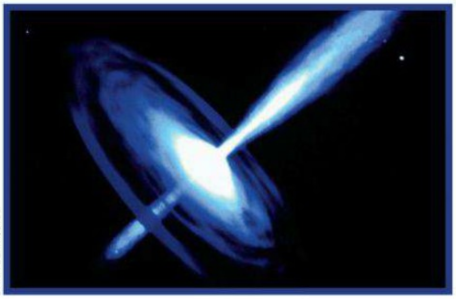
In 1916, German physicist Albert Einstein (1879–1955) revolutionized our understanding of the universe when he published his general theory of relativity. In it, he described the relationship between the fabric of space-time and the mass of celestial bodies. Space-time is the combination of three spacial directions (height, width, and depth) with the time dimension.

The easiest way to interpret gravitational interactions, Einstein said, is to think of the space-time continuum as a stretchable material that bends as massive objects "sit" inside it. While this two-dimensional analogy does not represent what is happening in four-dimensional space, it serves as a capable model.

When you stretch a pliable plastic sheet tautly, and you place a softball on it, the gravity well around the ball pushes the sheet downward and curves the fabric. The same thing happens in the four-dimensional universe. Near actual massive objects that have large gravitational pulls, the "fabric" of space-time curves and stretches.


ESA/NASA

GRAVITATIONAL-WAVE DETECTOR. The Laser Interferometer Space Antenna (LISA), planned for launch in 2015, will detect low-frequency gravitational waves. It will thus open a new window on the universe.


DANA BERRY/STScI

CENTRAL ENGINE. Black holes are important creators of gravitational waves. This artwork shows the central, supermassive one that powers the active galaxy PKS 0521–36.

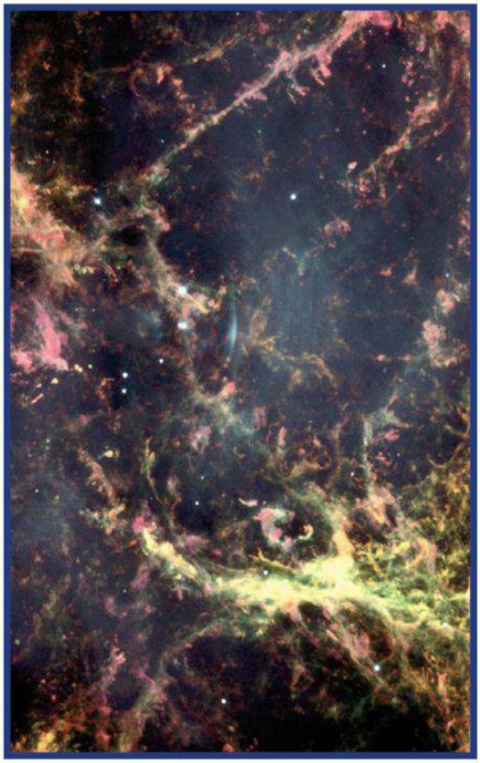
Massive objects also cause another effect in the fabric of space-time. Just as a boat creates waves on a lake as it slices forward through the water, stars and other bodies in the universe create ripples in the fabric of space-time. Astronomers call these ripples gravitational waves.

Massive objects like black holes create larger gravitational waves than less massive objects. Likewise, objects moving rapidly through space create more sustained gravitational waves than slower moving ones.

Although scientists have theorized gravitational waves for the better part of a century, studying them is really in its infancy. Astronomers know the interaction of two compact and massive bodies usually produces gravitational waves. Interactions may be merging galaxies, binary black holes, or neutron stars, or normal stars simply encountering each other.

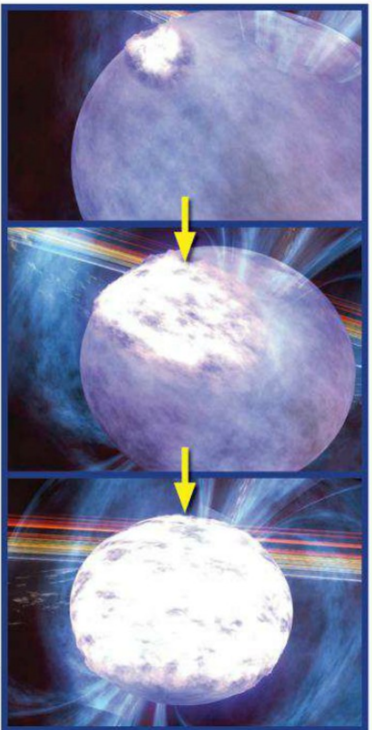
These interactions produce "ripples" in space-time. When this gravitational radiation finally reaches Earth, however, it is weak. Like waves in water, gravitational waves weaken as they move outward from their origin. So gravitational waves prove difficult to detect and interpret once they reach us from a variety of distant locations.

To help detect faint signals, astronomers turn to interferometry. Two large test masses placed a great distance apart serve as detectors. The masses are free to move in all directions, and lasers continuously measure the exact distance between them. When a gravitational wave passes through them, the ripple in space-time causes their distance to fluctuate slightly. It's an ingenious technique, and devices to measure gravitational waves are under construction in several places around the world.



WAVY BANG. Supernova explosions, like the one that produced the Crab Nebula (M1) in the constellation Taurus in 1054, are significant producers of gravitational waves. NASA/THE HUBBLE HERITAGE TEAM

Engineers are building the Laser Interferometer Gravitational Wave Observatory (LIGO), a joint project between the Massachusetts Institute of Technology and Caltech, in Hanford, Washington, and Livingston, Louisiana. In Italy and France,



DANA BERRY/STScI

SPINNING STAR. Gravitational waves originate from a variety of objects, including pulsars, rapidly-rotating neutron stars. Using NASA's Rossi X-ray Timing Explorer, astronomers found in 2003 the upper limit to a pulsar's spin, based on an outburst on a pulsar, shown in this series of illustrations.

astronomers at the European Gravitational Observatory are constructing the Virgo gravitational-wave detector. German and British physicists are working together to commence operations on the GEO 600 detector, which has been built near Hanover, Germany. Japanese astronomers are constructing TAMA300, a gravitational-wave detector project commenced in 1995.

Above all these Earth-based projects, NASA plans on launching the Laser Interferometer Space Antenna (LISA) in 2015. This project will provide the best observatory for detecting gravitational waves and will begin to give astronomers significant clues about the interaction of matter and space-time, and how the universe came to be.

27 What happens when **black holes** collide?

For more than 20 years, astronomers have considered an intriguing question: What happens when two black holes meet? Inside a galaxy, black holes that formed from dead, massive stars might encounter each other, especially in double or multiple star systems. No one has yet seen such a collision take place, but the subject is becoming a hot topic of theoretical astrophysics.

Studying the possibilities took a big step forward in 2004, when a team of astronomers — Marc Favata of Cornell University, Scott Hughes of the Massachusetts Institute of Technology, and Daniel Holz of the University of Chicago — authored a study that appeared in *Astrophysical Journal Letters*; this kicked off a number of other studies to create a burgeoning field.

It turns out astronomers think a funny thing happens when black holes collide. They spiral toward each other and merge into a single entity. A gravitational "slingshot" effect then violently whips them outside their host galaxies into intergalactic space. The ejection mechanism results from a byproduct of the merger: gravitational waves. The gravitational waves actually shoot the merged black hole far away from the site of its merger.

What role does this process play in building black holes? Could large numbers of black holes exist outside galaxies, where their presence would be extremely difficult to detect? These questions and others are currently on the table, and researchers are looking to build their knowledge of the subject. A real breakthrough would come from observing a binary black hole — a black-hole merger in the making.

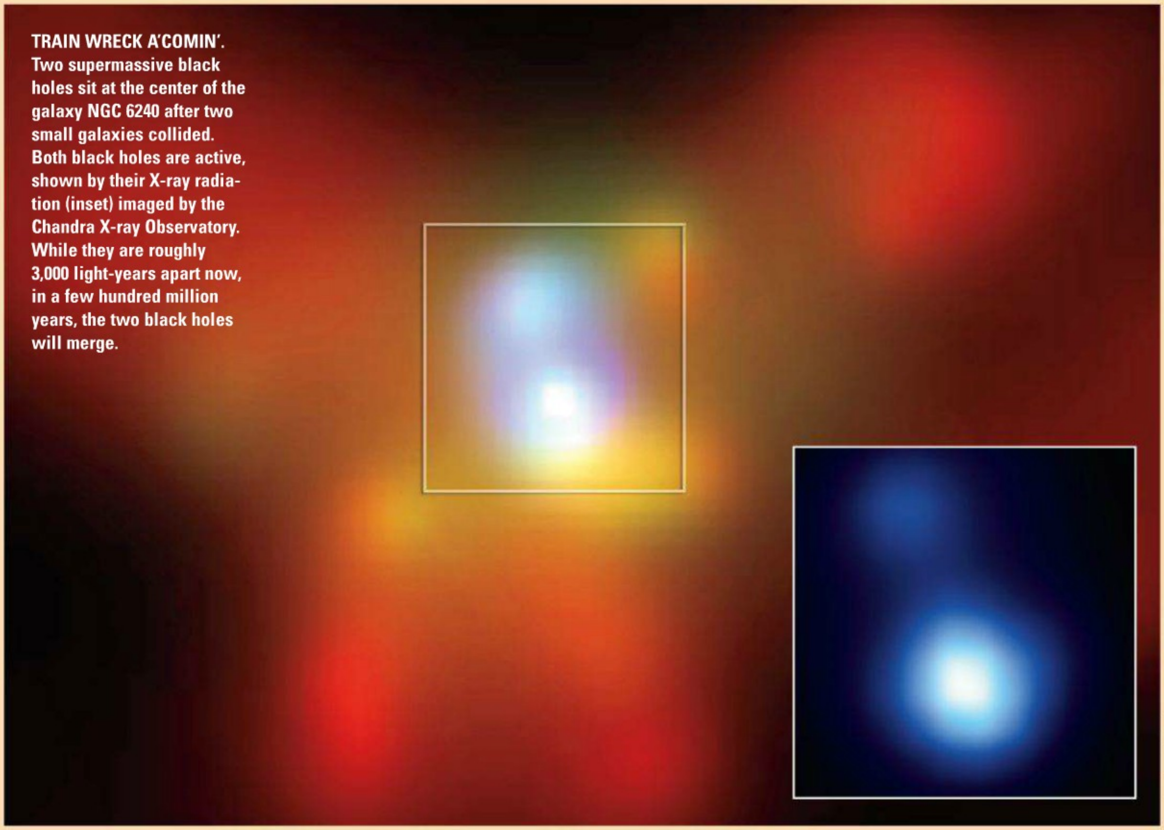
SDSS

BABY BLACK HOLE. The feeble light from a redshift 6.4 quasar (arrow) took roughly 13 billion years to reach our eyes. This image shows the quasar when the universe was just 800 million years old. Physicists are learning how the supermassive black hole that feeds the quasar got so big early in the universe.

"Almost all large galaxies contain black holes," says Hughes, "and galaxies merge like mad — especially a couple billion years ago." Hughes believes binary black holes could have formed and be forming yet today, but detecting them observationally will be difficult. "We're talking about two incredibly small bodies separated by a parsec," he says, merely 3.26 light-years in galaxies that span hundreds of thousands of light-years across.

Black holes escaping their parent galaxies would be shot out at high velocities, probably 685,000 mph (1.1 million km/h). Such high-speed objects eventually might join other nomadic black holes in deep space.

Such freeform black holes would prove elusive. "If they're not shining [from radiation produced by swallowing nearby bright material], it's hard to know where to look," according to Piero Madau of the University of California, Santz Cruz. The only way to



TRAIN WRECK A'COMIN'. Two supermassive black holes sit at the center of the galaxy NGC 6240 after two small galaxies collided. Both black holes are active, shown by their X-ray radiation (inset) imaged by the Chandra X-ray Observatory. While they are roughly 3,000 light-years apart now, in a few hundred million years, the two black holes will merge.

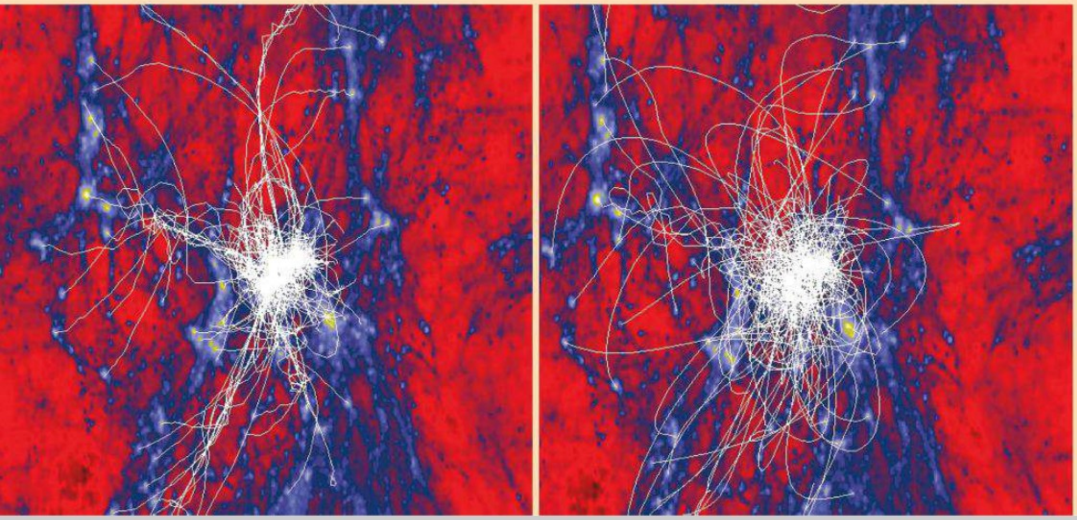
NASA/CXC/MPE/S. KOMOSSA ET AL.

detect intergalactic black holes would be from gravitational-lensing effects, and current telescopes are unable to do that.

Intergalactic black holes could absorb material without radiating, and so, continue along below the radar. "For that reason," says Mitch Begelman of the University of Colorado, "We can't rule out the possibility that black holes outside galaxies contain more mass than black holes inside galaxies."

The evidence for small black holes gone missing from normal galaxies does hold some potential. According to David Merritt of the Rochester Institute of Technology in New York, "As we look at ever smaller galaxies, there's a point where you stop seeing black holes." Merritt and other astronomers wonder if smaller galaxies may have had their small stellar black holes shot out into intergalactic space.

Studying black-hole mergers could pay off big dividends when it comes to understanding large black holes in the early universe. Do they form by the process of mergers or by gradual accretion? Observational tests for determining how big black holes formed in the early cosmos are lacking; perhaps looking at how smaller black holes behave in more recent times will shed light on this question.



SIMULATING SMASH-UPS. Astronomers can model black-hole kicks (which may eject them from galaxies) with computer simulations. In these, hundreds of primordial black holes live within dark-matter halos. Each image shows black-hole trajectories over billions of years — from redshift 8.16, when the universe was 600 million years old, to redshift 1, at an age of 6.5 billion years — based on different initial velocities. Yellow corresponds to high-density areas; red to low-density. TOM ABEL/MIROSLAV MICIC/STEINN SIGURDSSON

28

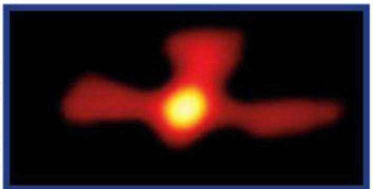
Why does antimatter exist?

In the earliest days of the universe, shortly after the Big Bang, the cosmos was awash in particles. Not all of them were normal particles of matter, however. Corresponding with each type of particle is an antiparticle with the same mass and spin.

The nature of our universe results from the fact that matter exists in slightly more quantity than antimatter. The difference is slight, however: For every billion particles of antimatter, there must have been a billion and one particles of matter in the early universe. Everything that exists — galaxies, stars, planets, trees, people — owes its existence to the slight surplus of matter.

The question of why antimatter exists and why matter is slightly more abundant dates to 1928, when British physicist Paul Dirac described the behavior of electrons. Dirac worked with quantum mechanics and relativity and worked out an equation governing how electrons should interact with other particles. Dirac's equation predicted that for every electron, there should be a corresponding antiparticle with the same mass but otherwise is a mirror image of the original.

In 1932, American physicist Carl D. Anderson observed a particle track, caused by a cosmic ray, that appeared to be "something positively charged, and with the same mass as an electron." Following a year's worth of experiments, Anderson determined anti-electrons exist, dubbed them positrons, and won the Nobel Prize in physics for the effort.



W. PURCELL ET AL./OSSE/COMPTON OBSERVATORY/NASA

BIZARRO MILKY WAY. The center of the Milky Way contains a glowing cloud of gamma rays. Antimatter particles annihilating matter create the energetic jet.

Twenty years later, physicists discovered anti-protons and anti-neutrons while conducting experiments with the Bevatron particle accelerator at the University of California-Berkeley. In 1968, scientists first produced anti-atoms, and in 1995, near Geneva, Switzerland, physicists created antihydrogen atoms that lasted long enough for scientists to study their behavior.

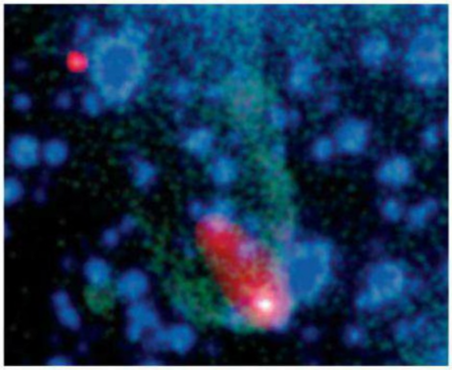
These experiments still do not enable astronomers to explain the asymmetry of matter to antimatter. Other important physics experiments with particle colliders and other methods are planned for the future. How could matter now be so dominant? One idea is that primordial black holes, which formed in the infant universe, may have evaporated and thus thrown the symmetry askew. Another group of physicists believes the asymmetry lies in the category of particles called leptons, which includes neutrinos and muons.

Neutrinos seem to be the leading culprit. Austrian physicist Wolfgang Pauli developed the idea of neutrinos in 1930, when he was desperately searching for an explanation of the process called beta decay.

In beta decay, a neutron disintegrates into a proton and an electron plus something else — the neutrino. Because neutrinos interact minimally with other matter, they are very difficult to diagnose.

Countless numbers of neutrinos produced within the Sun's core pass through us every second. A number of physicists believe heavy neutrinos existed in the early universe that might have decayed, tipping the scales far toward matter.

Whatever the reason for such a small quantity of antimatter in today's universe, it is out there. Tiny quantities of antimatter rain down from cosmic rays and are quickly evaporated by interactions with matter.



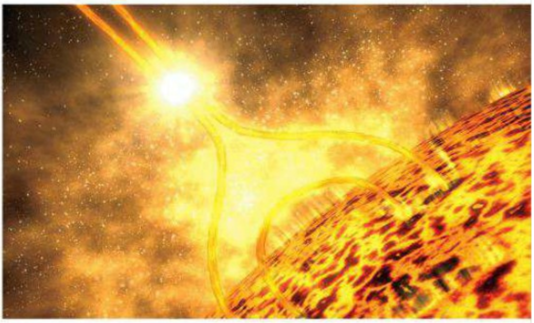
NASA/CXC/ASTRON/B. STAPPERS, ET AL/AAO/J. BLAND-HAWTHORN/H. JONES

ANTIMATTER JET. The Chandra X-ray Observatory imaged the "Black Widow Pulsar" in 2003. The photo reveals a rejuvenated pulsar emitting a high-speed beam of matter and antimatter particles.

Anywhere high-energy collisions take place, antimatter is sure to be there. The powerful black hole in the center of the Milky Way produces an antimatter jet. The boundary where the antimatter collides with normal matter produces gamma rays.

Antiparticles get made where the temperature is extremely high — for example, the event horizon of a black hole. Should we ever get to the point of traveling deep into space, hazards from antimatter, which annihilates matter when the two collide — would pose a real and somewhat unpredictable hazard.

POWER BLAST. Explosions on the Sun blast antimatter from the solar surface in this illustration. The largest eruptions on the Sun can unleash as much energy as a billion one-megaton bombs. In July 2002, a solar flare released about one pound of antimatter, enough energy to power the United States for 2 days.



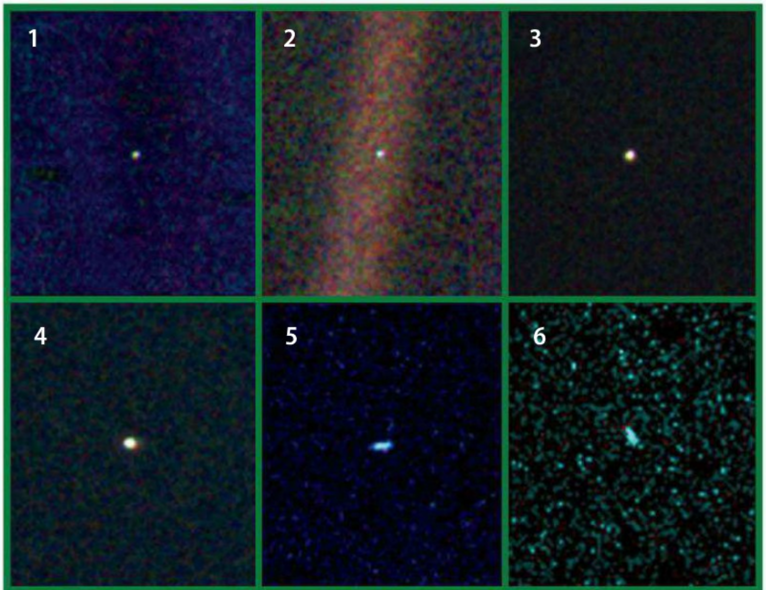
NASA

29 Are there **other planets** like **Earth**?

One of the astonishing breakthroughs in observational astronomy of the 1990s was detecting the first planets outside our solar system. As of November 2006, astronomers had found 210 extrasolar planets in 180 different planetary systems. The bulk of these planets are massive Jupiter-sized worlds. As of yet, technology does not allow astronomers to find distant earthlike planets around other stars. But that's not to say the search for such worlds hasn't begun.

Despite the fact that earthlike planets have not yet been found, astronomers feel there's good reason to think many exist. The history of extrasolar-planet discoveries around ordinary stars reaches back to 1995, when astronomers detected a planet circling the star 51 Pegasi. The planet is a gas giant more massive than Saturn that orbits its star every 4.2 days. The planet is so close to its star (Mercury orbits the Sun every 88 days), that astronomers termed it and many other massive, close-orbiting planets they began to find "hot Jupiters."

The discoveries of 51 Pegasi's planet and others like it puzzled astronomers, at first, because, as they understood solar system formation, gas giants formed on the outer fringes, not close in to stars. How could hot Jupiters form so close to their stars, when the star's heat would presumably destroy the planet's gases before they came together to make a planet? In addition to the puzzling results on large planets, astronomers found no smaller planets similar to Earth in their searches.



FAMILY PORTRAIT. In these six portraits taken by the outbound Voyager 1 (launched September 5, 1977) spacecraft in 1990, six planets are visible. Starting at top left, they are: 1) Venus, 2) Earth, 3) Jupiter, 4) Saturn, 5) Uranus, and 6) Neptune. NASA

GOOD ECOBALANCE. Earth affords life all the right luxuries — moderate temperatures, lush vegetation, and abundant water. This is a photo of the United States' Great Lakes region.

SEAWIFS PROJECT

But, recently, the trend has reversed. With new technology and new planet-searching techniques, astronomers have found planets smaller than the hot Jupiters. It's becoming clear that hot Jupiters, once thought to be the norm, are actually the exception.

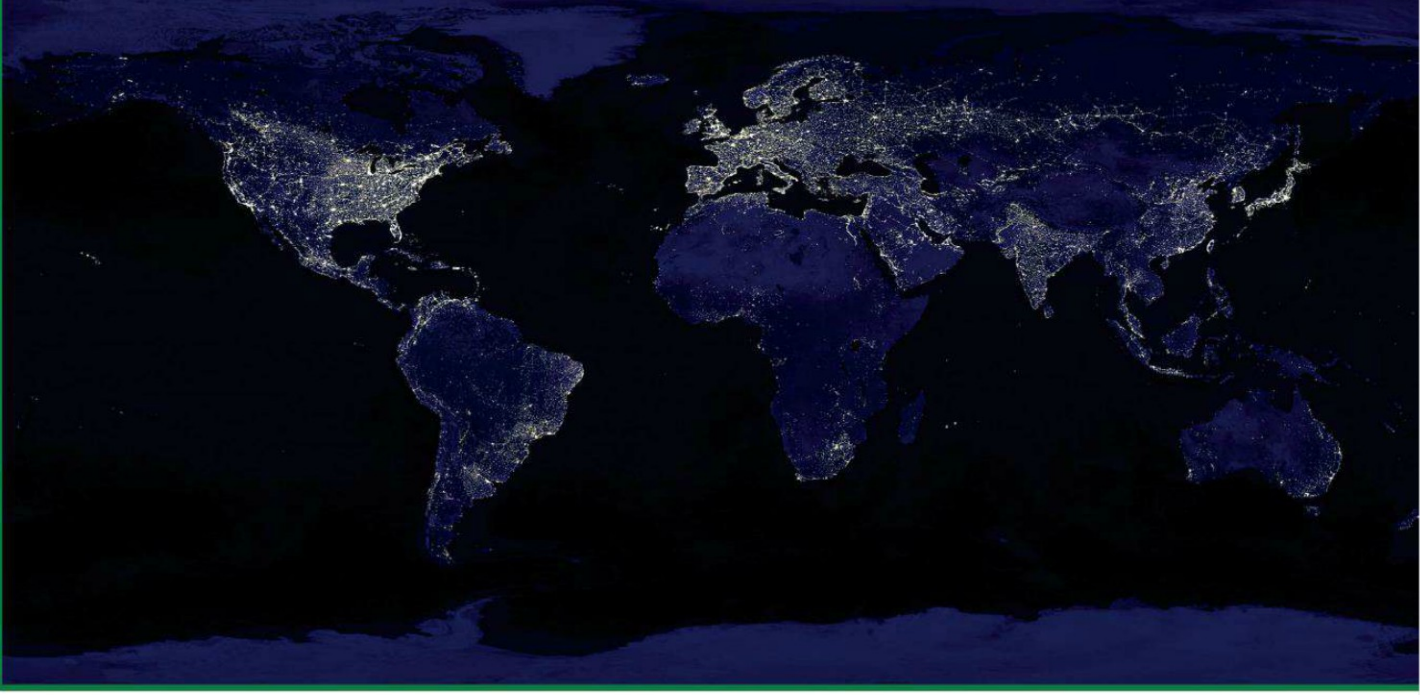
As the list of extrasolar planets grows, astronomers are discovering a lot about what it takes to host a planetary system. For example, more massive stars are more likely to have planets than lighter ones.

M dwarfs, which have masses 1⁄10 to 1⁄3 of the Sun's, seem to lack planets entirely. K-type stars, with masses of 1⁄3 to 2⁄3 the mass of the Sun, have only a small number of planets — about 3 to 4 percent of the time.

G-type stars like the Sun, thus far, show planets 7 percent of the time. The leaders, with 10 percent of their type bearing planets, are F stars — 30 to 50 percent more massive than the Sun.

Additionally, single stars (in the minority) are the best hosts for planetary systems. Relatively few binary systems seem to have planets orbiting them. And the chemistry of stars matters, too: Stars rich in metals, elements heavier than hydrogen and helium, are better hosts for planetary systems than less evolved stars.

The search for extrasolar planets has sharpened astronomers' views of how solar systems form. The leading model, called



core accretion, suggests a rotating planetary disk settles around a young star, and then billions of collisions in the disk cause particles to clump together. As more and more particles stick together, protoplanets several miles across eventually form, and they become planetary cores.

The process happens relatively quickly in the inner part of a solar system, where rocky-planet building takes place. Terrestrial planets like those in our solar system could come together in as little as 100,000 years. But the creation of gas giants is not well explained in the core-accretion model. The gravitational-instability model is an alternative, less popular, idea. This says instabilities form as a disk collapses, leading to the clumping together of matter into planets. Neither idea yet addresses one surprise from the exoplanet-discovery program: the fact that nearly all exoplanets have orbits that are far more eccentric than those of the planets in our solar system.

Despite the mysteries, explanations of exoplanets are getting better by the month, as discoveries increase. The best places to find them are in the younger, metal-rich areas of spiral galaxies. Planets are most likely found in the galaxy's arms, and in the less chaotic regions of them.

The best stars to look at are those of G and F spectral types. Perhaps the best tip for exoplanet searchers is to keep looking. In 2007, the European Space Agency will launch the Kepler mission. The onboard instruments will search more than 100,000 stars for transits of earthlike planets. In 2009, NASA's Space Interferometry Mission will look for earthlike planets around the nearest 100 stars. A proposed Terrestrial Planet Finder, which may or may not achieve funding, was slated for launch in 2014. It would detect light from earthlike planets within 45 light-years of home.

▲ **BIG GLOW. Earth's nighttime city lights glow as recorded from space by a United States Department of Defense Meteorological Satellite. Could civilizations on planets surrounding other stars likewise be casting light into the darkness? It soon may be possible to detect such light originating on other worlds.** NASA

▼ **HEAVY SMOKER. Popocatépetl, or Popo, sends a plume of smoke skyward January 23, 2001, as imaged from the space shuttle. The Aztecs gave the mountain the name Popocatépetl, which means "smoking mountain." Other Earth-like planets may produce similar smoke plumes.**

NASA

30

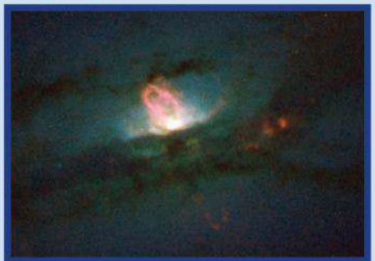
Does every big galaxy have a central black hole?

In the early 1960s, astronomer Maarten Schmidt of the California Institute of Technology made a breakthrough discovery. Looking at several stars that were strangely bright at radio wavelengths, Schmidt obtained a spectrum of the "star" 3C 273 and found its distance to be extremely large. It wasn't a star at all, but a remote, extraordinarily energetic object that looked like a star — a quasi-stellar object, or quasar.

For many years, the mystery of exactly what quasars were remained unsolved. They baffled astronomers at every turn: Their spectral lines were shifted by an incredible amount toward the red end of the spectrum; because of their great brightnesses, they must represent the brightest objects in the universe, astronomers deduced. But what could be causing such an amazing outpouring of energy, apparently so early in the cosmos' history?

The first quasar identified, 3C 273, lies in the constellation Virgo 2 billion light-years away. But at this tremendous distance, it still glows brightly enough to be viewed with amateur telescopes in the backyard. How could an object that looks like a star be producing several thousand times the entire energy output of the Milky Way Galaxy?

Oddly, astronomers found these objects vary their light outputs over months or even days, so they had to be relatively small objects, too. As searches for quasars picked up steam, astronomers found many more of them. They found many star-like objects with colors different from those of stars and point sources associated with X-ray emission or strong radio output.

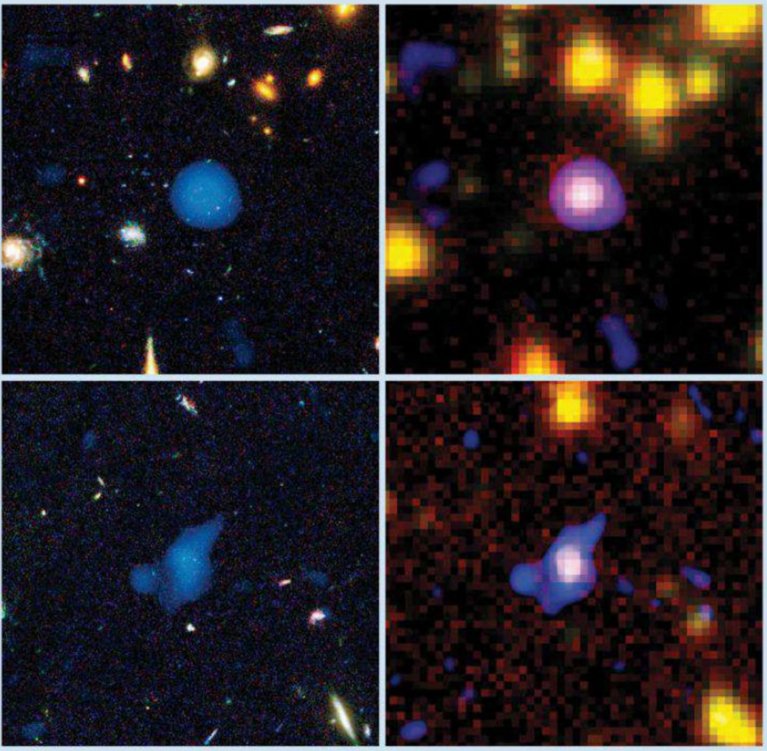


COSMIC BELCH. A hungry black hole in the center of the galaxy NGC 4438 blows hot bubbles of gas into space in this Hubble Space Telescope image. The bubbles arise as the black hole consumes material falling into it.

NASA/JEFFREY KENNEY/ELIZABETH YALE

Now, 40 years after the discovery of 3C 273, the latest catalogs contain more than 13,000 quasars, a number that — thanks to systematic surveys like the Sloan Digital Sky Survey — should eventually reach 100,000.

Years into the quasar puzzle, in the late 1970s and 1980s, astronomers began to get a handle on what these objects might be. Quasars fit into a classification of a large number of seemingly related objects called active galactic nuclei, or AGN. Now astronomers realize that, clearly, all types of active



NASA/ESA/A. M. KOEKEMOER/M. DICKINSON/THE GOODS TEAM

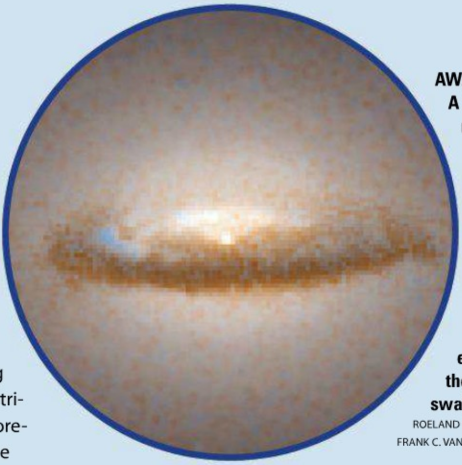
HIDDEN MONSTERS. Distant galaxies imaged in the Hubble Space Telescope's GOODS field (a special deep field) reveal massive galaxies in the two left images; the right-hand counterparts show the glow of powerful black holes as revealed by the Spitzer Space Telescope.

galaxies — quasars, Seyfert galaxies, BL Lacertae objects, radio galaxies, and other weird entities — have one thing in common: They are all driven by powerful central black holes. Material falling into a central-engine black hole — stars, gas, and dust — gets spun quickly and creates high-powered jets of radiation that produce the amazing output we see as a quasar.

More recently, in the 1990s, astronomers realized AGN are really different shades of the same creature, some appearing like different animals because of different orientations to our line-of-sight along with other geometrical differences. Moreover, Hubble Space Telescope data continued turning up huge numbers of monster black holes in the centers of many galaxies — even "normal" galaxies like the Andromeda Galaxy and the Milky Way. Soon, a general picture emerged of how quasars and black holes fit into the cosmos.

The idea came forward that most galaxies other than dwarfs have central black holes. The idea is that black-hole "seeds" either attracted matter into forming galaxies or formed within young galaxies and acted as powerful, hungry engines in the early universe. This action produced quasars and explains why most quasars are extremely distant. As the black hole "ate" more and more matter from galaxies' centers, little fuel remained for them to feast upon nearby, so they slowly quieted down. Most galaxies in the recent universe have slumbering giants in their centers.

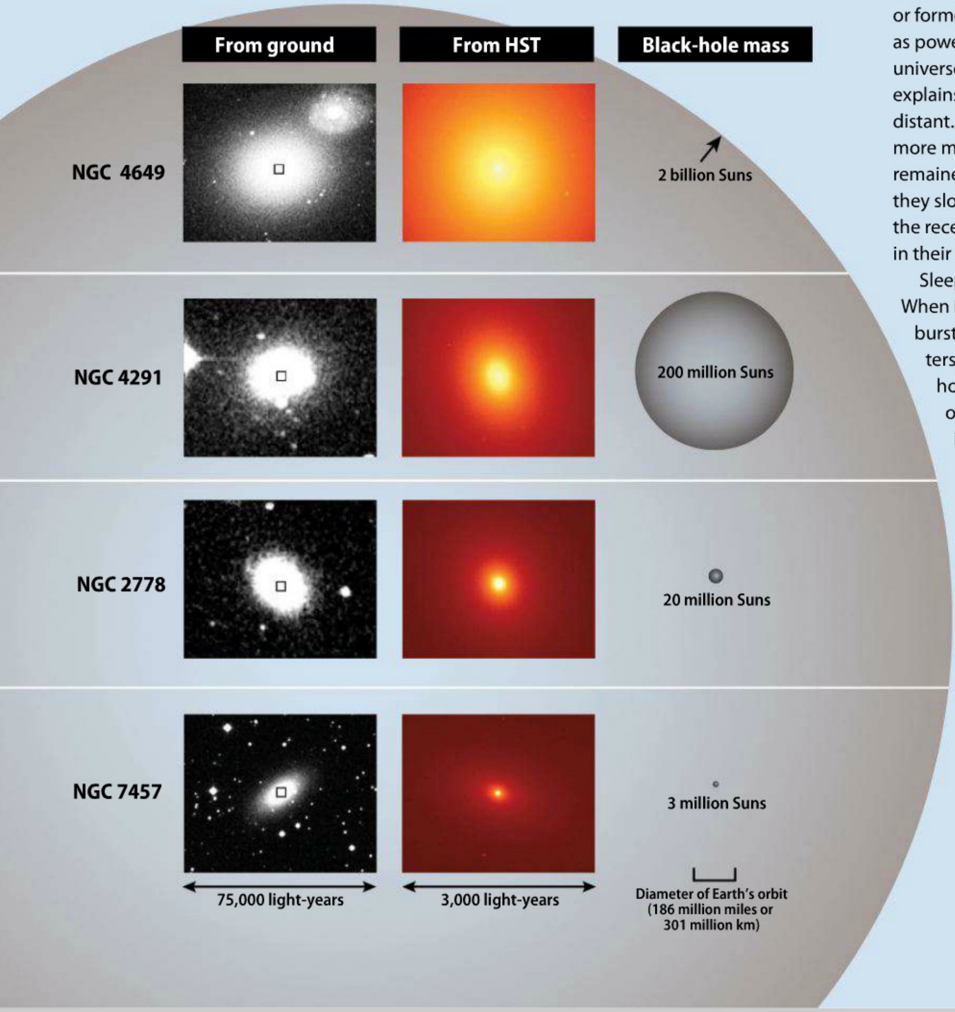
Sleeping giants can awake, however. When interactions with other galaxies, starbursts, or gas clouds falling into the centers of galaxies "wake up" central black holes, they can erupt again with an outburst of energy. This explains AGN in the nearby universe. The prevailing notion, then, is that most large galaxies contain big black holes, the majority of which are asleep after a wild youth.



AWAITING LUNCH. **A 300-million solar-mass black hole lies within the elliptical galaxy NGC 7052. This Hubble image shows the galaxy's thick, dark dust band, which enshrouds the black hole. In several billion years, the black hole will swallow this feature.**

ROELAND P. VAN DER MAREL/ FRANK C. VAN DEN BOSCH

Black hole mass scales with galaxy size



ONE SIZE DOESN'T FIT ALL. The hearts of four massive elliptical galaxies show that the more massive a galaxy's central bulge, the more massive its black hole. The black-and-white images at left show the galaxies; close-ups taken with the Hubble Space Telescope fill the middle column. The right-hand column illustrates the corresponding black-hole masses.

NASA/KARL GEBHARDT

31 Does inflation theory govern the universe?

Ever since the Big Bang theory of the origin of the universe was proposed in 1927, the idea has had its skeptics. The radical concept stated that the universe is expanding; run time backwards, and all matter and energy intersect at a point in time 13.7 billion years ago, the moment of the "bang."

Big Bang cosmology has received enormous support from observational tests. In 1929, American astronomer Edwin Hubble observed galaxies generally recede from us; that was the lynchpin of the evidence.

In 1964, Bell Laboratories physicists Arno Penzias and Robert Wilson discovered the faint echo of the Big Bang — the cosmic microwave background radiation (CMB). Along with the expansion of the universe and the CMB, nucleosynthesis, the process by which light elements formed in the early universe, is explained by the Big Bang model.

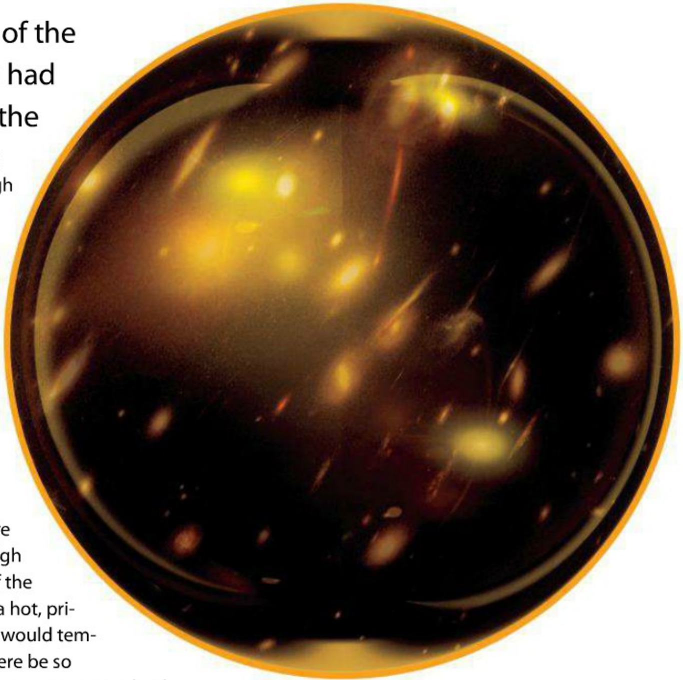
But the Big Bang does not yet explain it all. Although by the 1970s the Big Bang seemed to outweigh competing ideas about the formation of the cosmos, it left some problems unsolved.

The first was causality. To astronomers' amazement, they found the CMB's temperature was uniform everywhere they looked, to a high level of precision. If the universe began as a hot, primeval fireball, why would temperatures everywhere be so uniform? Leaving this enigma unsolved would threaten the Big Bang idea.

Second came the flatness problem. The cosmological number Omega (Ω) describes both the universe's shape and fate. Astronomers found Omega's value equals 1, which seemed highly coincidental. A number less than 1 would mean space is open and will expand forever; greater than 1 would mean a closed universe and an eventual "Big Crunch," with the cosmos falling back on itself.

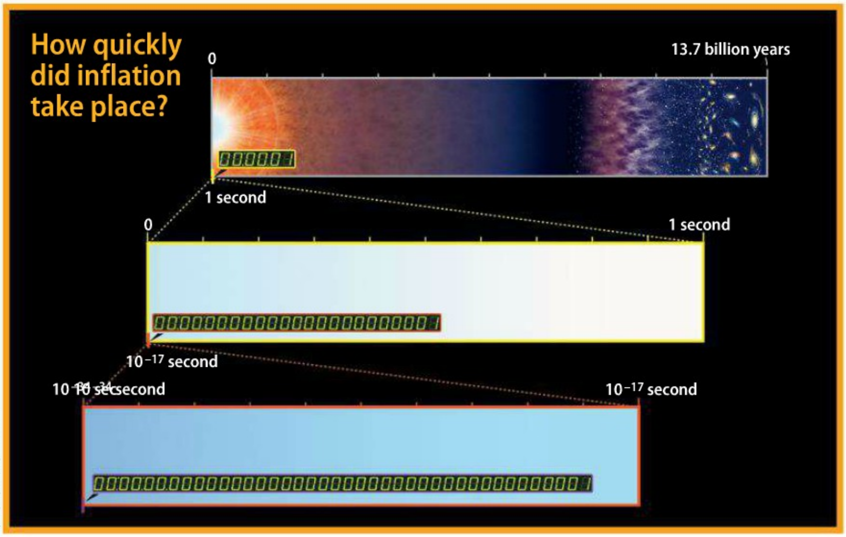
Third was the magnetic monopole problem. The cosmos is filled with electric monopoles, particles like electrons and protons. But astronomers have not observed any magnetic monopoles. The lack of these particles bothered particle physicists.

In 1981, to solve these problems, scientists presented a new idea that expanded the Big Bang theory and added weight to it. Alan Guth of the Massachusetts Institute of

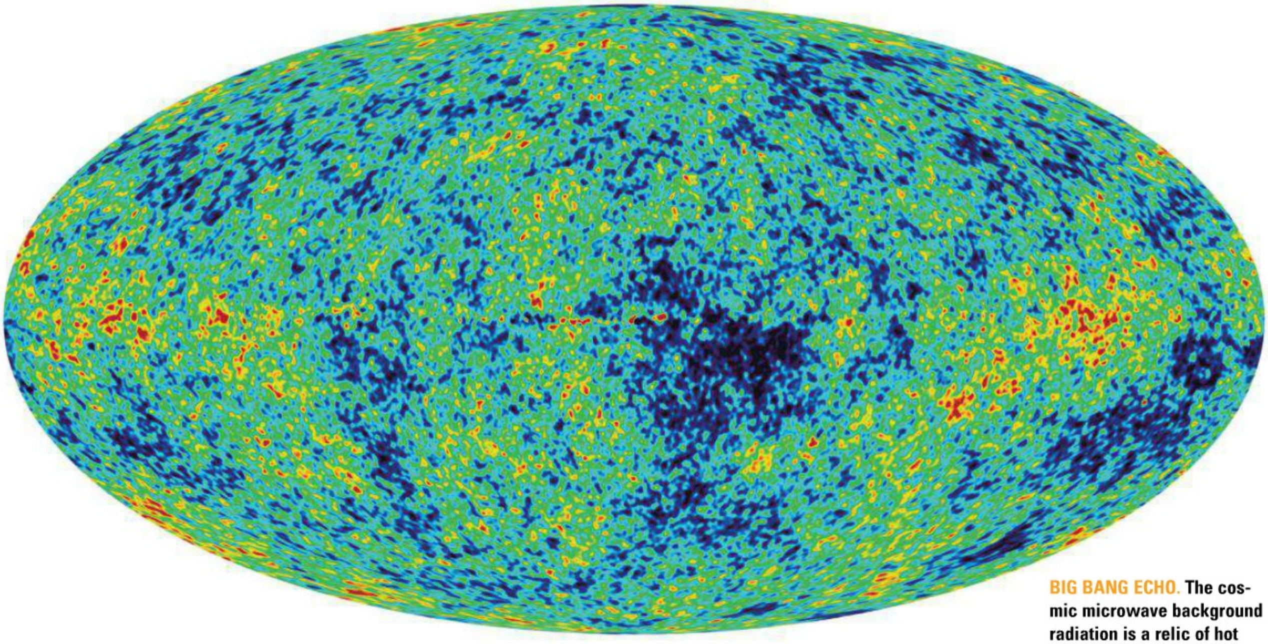


▲ **TINY COSMOS. This artist's conception shows the universe at actual size, immediately after the period of hyperexpansion known as inflation.** *ASTRONOMY:* ROEN KELLY AND CHUCK BRAASCH

MINUSCULE TIME. How much is 10^{-34} second? To get an idea, compare 1 second to the 13.7-billion-year age of the universe. Next, divide that 1 second into an equivalent number (13.7 billion) of parts to get 10^{-17} second. Repeat that step one more time, and you'll get back to inflation's beginning.



ASTRONOMY: ROEN KELLY



BIG BANG ECHO. **The cosmic microwave background radiation is a relic of hot radiation emitted when atoms first formed and light could travel freely, 380,000 years after the Big Bang. The smoothness of this radiation suggests the universe expanded at breakneck speed in the first fraction of a second. (Different colors show temperature differences of a few millionths of a degree.)**

NASA/WMAP SCIENCE TEAM

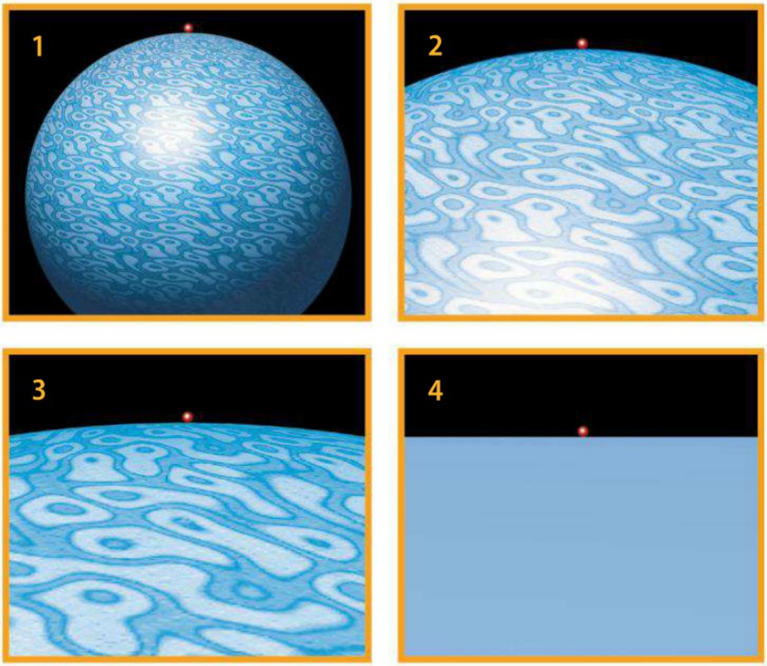
Technology wrote a paper that described the "inflationary" model of cosmology, developed with his colleagues Andrei Linde, Paul Steinhardt, and Andy Albrecht.

Inflation proposes a short period of expansion — 10^{-34} second — in the early universe. As Mario Livio of the Space Telescope Science Institute says, "All inflation theories … grab a speck of space and blow it up by a factor of 10^{50}." Inflation resolves some questions surrounding the Big Bang.

Guth and his colleagues imagined a huge energy field in the early universe, which they called the false vacuum. As it expanded, the false vacuum was in a perilous state of equilibrium, and it had to decay into a real vacuum, leading to an enormous release of energy. Inflation resulted from the decay. The released energy acted as an antigravity force, giving the universe a kick. The universe exploded by many factors in an instant.

Viewed as a radical concept when Guth's paper was published, the idea has received substantial support from a vast number of astrophysicists since. And observational tests of the Big Bang all have supported the theory. In 1992, the Cosmic Background Explorer (COBE) satellite discovered temperature fluctuations in the CMB, further evidence of the Big Bang. Later, the Wilkinson Microwave Anisotropy Probe (WMAP) refined this picture, adding weight to it. Other verifications of the Big Bang have helped convince skeptical astronomers that it occurred.

In the first years of a new century, evidence suggests the Big Bang occurred and that inflation was a key component of the cosmos' earliest moments. ▣



INFLATIONARY STEP. **Inflation made the universe flat. Here, a curved surface expands by a factor of 3 in each panel, appearing nearly flat by the end. To relive cosmic inflation, repeat this expansion 87 more times.**

ASTRONOMY: ROEN KELLY

32

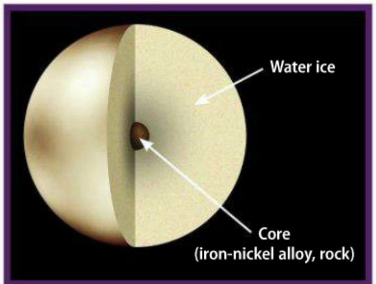
Should **Pluto** be considered a **planet**?

Ever since Neptune's 1846 discovery by German astronomer Johann Galle, discrepancies in its orbit suggested another planet existed far beyond it. Thus, the search for Planet X began, with "X" representing "unknown." Astronomers at many institutions responded, but none with the vigor of American philanthropist Percival Lowell, who determined his observatory should be responsible for finding the next new world. In 1930, an extensive search at Lowell Observatory in Flagstaff, Arizona, by the young American astronomer Clyde Tombaugh paid off when he found images of the new planet on two separate photographic plates, revealing its motion against the background stars.

Astronomers had found Planet X, now called Pluto (after the Roman god of the underworld). However, after analyzing the new planet's orbit, astronomers declared Pluto had too little mass to affect Neptune's orbit. It seems the discrepancies in Neptune's orbit arose from poor estimates of its mass. But the solar system then contained nine planets, and everyone was happy.

Pluto's planetary death blow came August 24, 2006, at the IAU meeting.

In 1978, James W. Christy, an astronomer at the U.S. Naval Observatory, discovered a "bulge" on a high-resolution image of Pluto and identified it as a large moon, which he named Charon. Pluto was now a double planet: Pluto itself measures about 1,485 miles (2,390 kilometers) across, Charon some 700 miles (1,127 km) across. Like Earth's Moon, Charon has a large diameter relative to its parent planet.



LPI

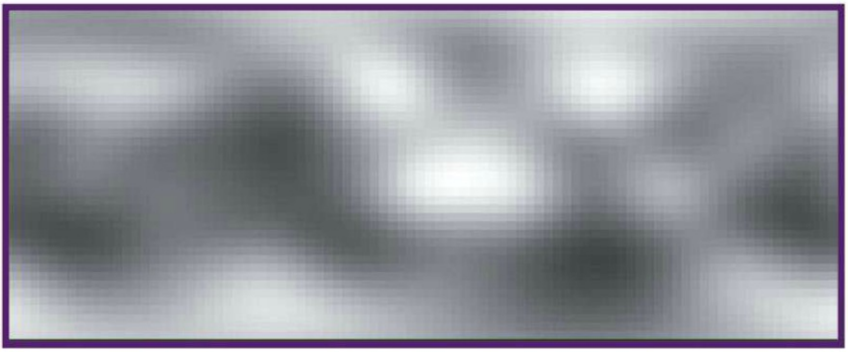
FROZEN WORLD. **Pluto's internal structure is not well understood, but it probably consists of an iron-nickel core, water ice, and large amounts of methane ice.**

The happy, nine-planet solar system began to unravel in the early 1990s, however. Planetary scientists found large numbers of objects in the Kuiper Belt, a region of the solar system beyond Neptune. These Kuiper Belt objects (KBOs), also called trans-Neptunian objects (TNOs) — a vast population of asteroids — promised to be numerous. Many thousands of TNOs probably exist (more than 1,200 have been discovered through 2006), and some are large bodies. Further, Pluto has a 2:3 orbital resonance with Neptune (Pluto's orbital period is 50-percent longer than Neptune's). Some large TNOs with the same resonances have been found and dubbed "plutinos." The firestorm of TNO discoveries fueled a heated debate over whether Pluto itself should be considered a planet.

The "controversy" grew in the mid- to late-1990s as media picked up on the story,

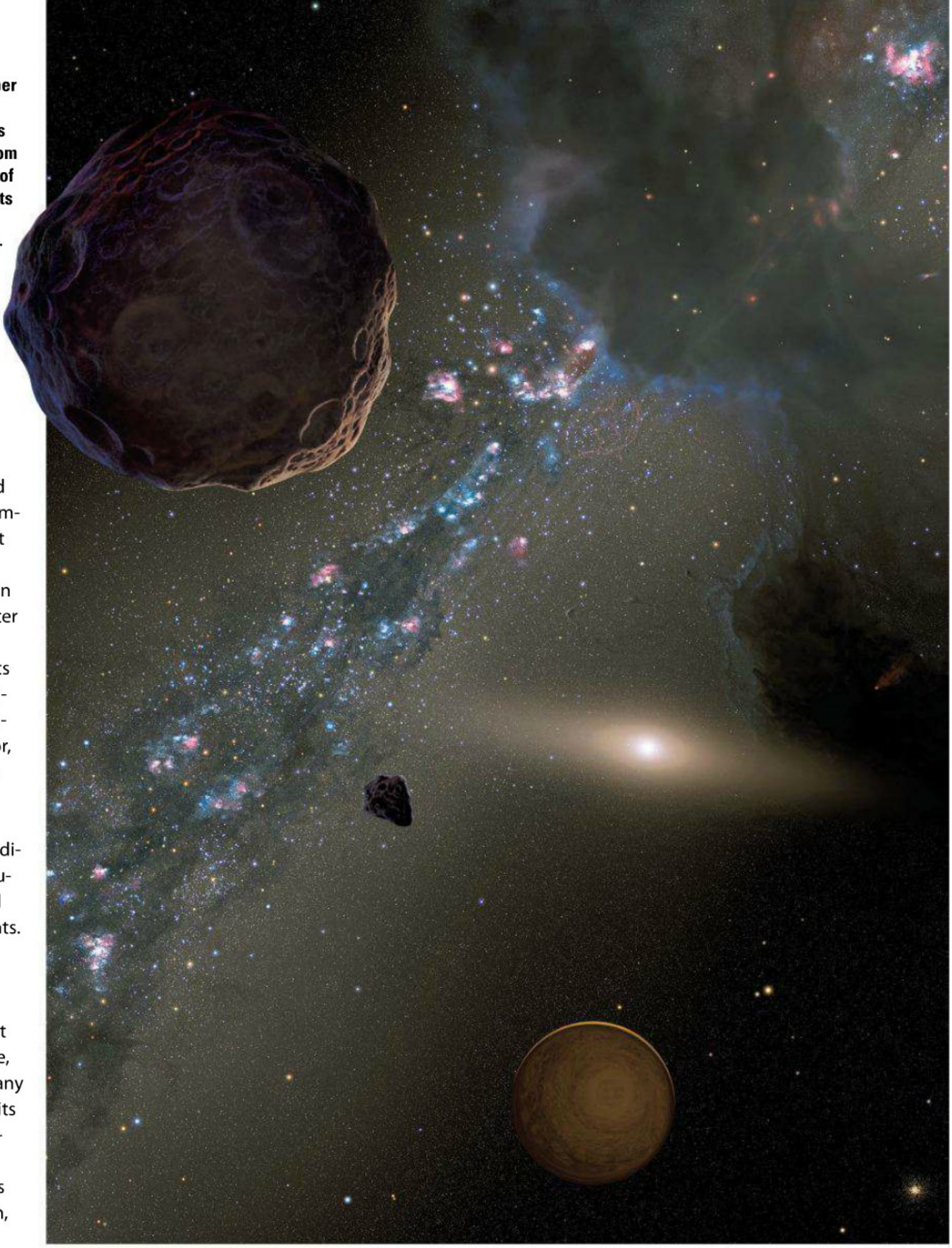
R. ALBRECHT/ESA/ESO/NASA

▶ **PLUTO'S BEST.** **The Hubble Space Telescope's best portrait of Pluto and its largest moon, Charon, show the pair as a fuzzy, orangish set of disks.**



NASA

PLUTONIAN MAP. **Pluto's surface, seen at the highest resolution thus far, was made with Hubble Space Telescope imagery. It shows Pluto has a dark equatorial band and bright polar caps; there may be basins and fresh impact craters on its surface.**



PLANET HAVEN. **The Kuiper Belt begins at Neptune's orbit and extends 50 times the Earth-Sun distance from the Sun. Here, thousands of potential Pluto-like objects formed early in our solar system's history. The largest may surpass Pluto in size.** ADOLF SCHALLER

and editorials, television, the Internet, and other venues joined in the fracas. In 1999, Brian G. Marsden, director of the International Astronomical Union's Minor Planet Center, the official naming body, joked that with the then-10,000th asteroid naming, Pluto should be awarded that number and given "dual citizenship" as a planet and an asteroid.

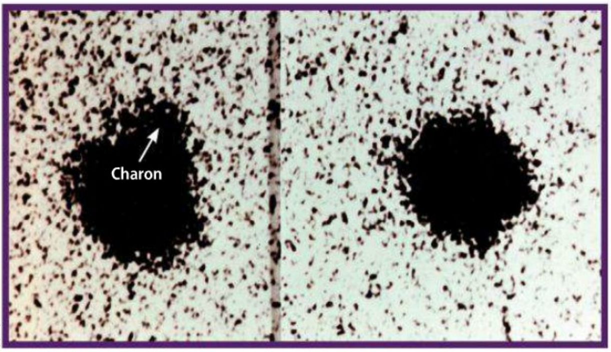
The issue seemed to culminate when, in 2000, New York's newly opened Rose Center for Earth and Space, home of the Hayden Planetarium, categorized Pluto in one of its exhibits as a sub-planet. "There is no scientific insight to be gained by counting planets," said the Hayden Planetarium's director, Neil de Grasse Tyson, "eight or nine — the numbers don't matter."

Amazingly, the volatile response from schoolchildren across the United States indicated the number did matter. Upset by Pluto's apparent demotion, they campaigned hard against any such nonsensical thoughts.

The whole issue raises the question of what exactly makes a planet? The word comes from the Greek for "wanderer," and the modern definition depends somewhat on the emphasis placed on an object's size, orbit, or origin. Under the argument that any body large enough to be spherical under its own gravity should be a planet (at a diameter of about 200 miles [320 km]), Pluto would be counted as a planet — as well as moons like Ganymede, Titan, Earth's Moon, and the largest asteroids.

The discovery that Pluto is a wandering TNO and that many similar bodies exist argues against its status as a major planet. Since 2002, large TNOs named Quaoar, Orcus, Sedna, and Eris have been found — Eris, at least, may be larger than Pluto.

Pluto's planetary death blow came August 24, 2006, on the final day of the International Astronomical Union's meeting in Prague. The remaining 424 members voted to strip Pluto of major-planet status and place it in a new category — dwarf planet.



USNO

NEW MOON. **In 1978, astronomer James W. Christy at the U.S. Naval Observatory discovered Pluto's largest moon, Charon. As the moon revolves around Pluto, it reveals itself as a "bump" on Pluto's dark disk (left). No bump appears (right) when Charon is in front of, or behind, Pluto.**

33 Why did **Venus** turn itself **inside-out**?

Years ago, planetary scientists thought of Venus as Earth's sister planet. Similar in size, both close to the Sun, both rocky bodies, Earth and Venus were practically considered two of a kind. That abruptly changed, however, when astronomers got their first close-up look at Venus. The moment arrived in 1962, when Mariner 2 flew by the planet, and far more forcefully in 1970, when Venera 7 touched down on the hellishly hot surface. Not only do surface temperatures on our sister planet exceed 750° F (400° C), but Venus' thick carbon-dioxide atmosphere produces a greenhouse effect that hosts sulfur-dioxide and sulfuric-acid clouds. It's not a friendly environment for living things of any sort.

VOLCANIC VENUS. Volcanoes in a region on Venus called Guinevere Planitia lowland suggest thick, sticky lava oozed from a point at the surface here. The center volcano spans 31 miles (50 km).

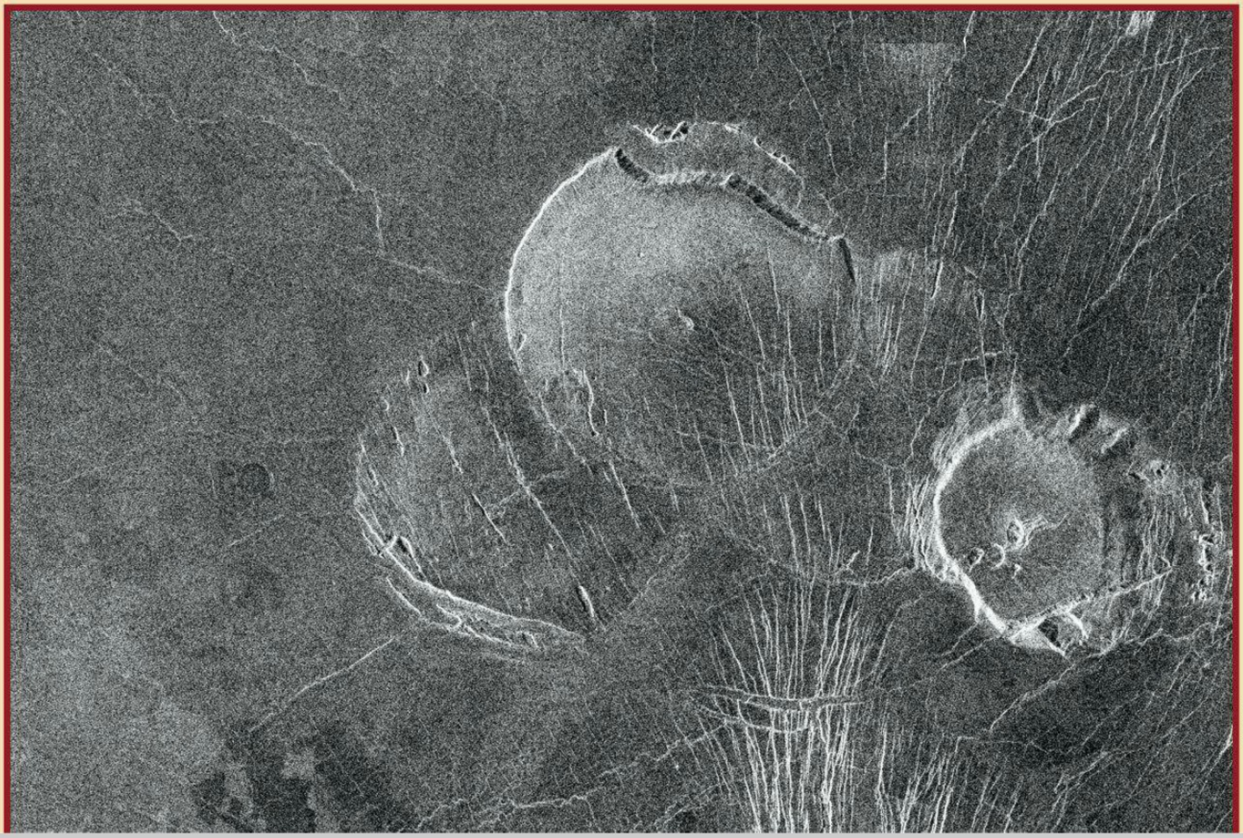
Scientists' understanding of Venus and its geology catapulted forward with the most significant mission thus far, the Magellan spacecraft. It arrived in venusian orbit in 1990 and continued to collect data through 1994.

Magellan mapped 98 percent of the planet's surface and returned thousands of spectacular views of Venus' geological features. Almost one-quarter of the images returned by Magellan became computerized, 3-D images of regions with altitude effects exaggerated by the image processors. For the first time, humans had a good look at what Venus is really like.

Surface temperatures on our sister planet exceed 750° F (400° C).

There were surprises. The most amazing was the relative lack of craters compared with other inner solar system bodies like the Moon, Mars, and Mercury. Water, wind, volcanoes, and tectonic shifts constantly resurface our planet. Venus must be hiding many old craters, too. Astronomers wondered what resurfacing forces could keep Venus' surface looking so young.

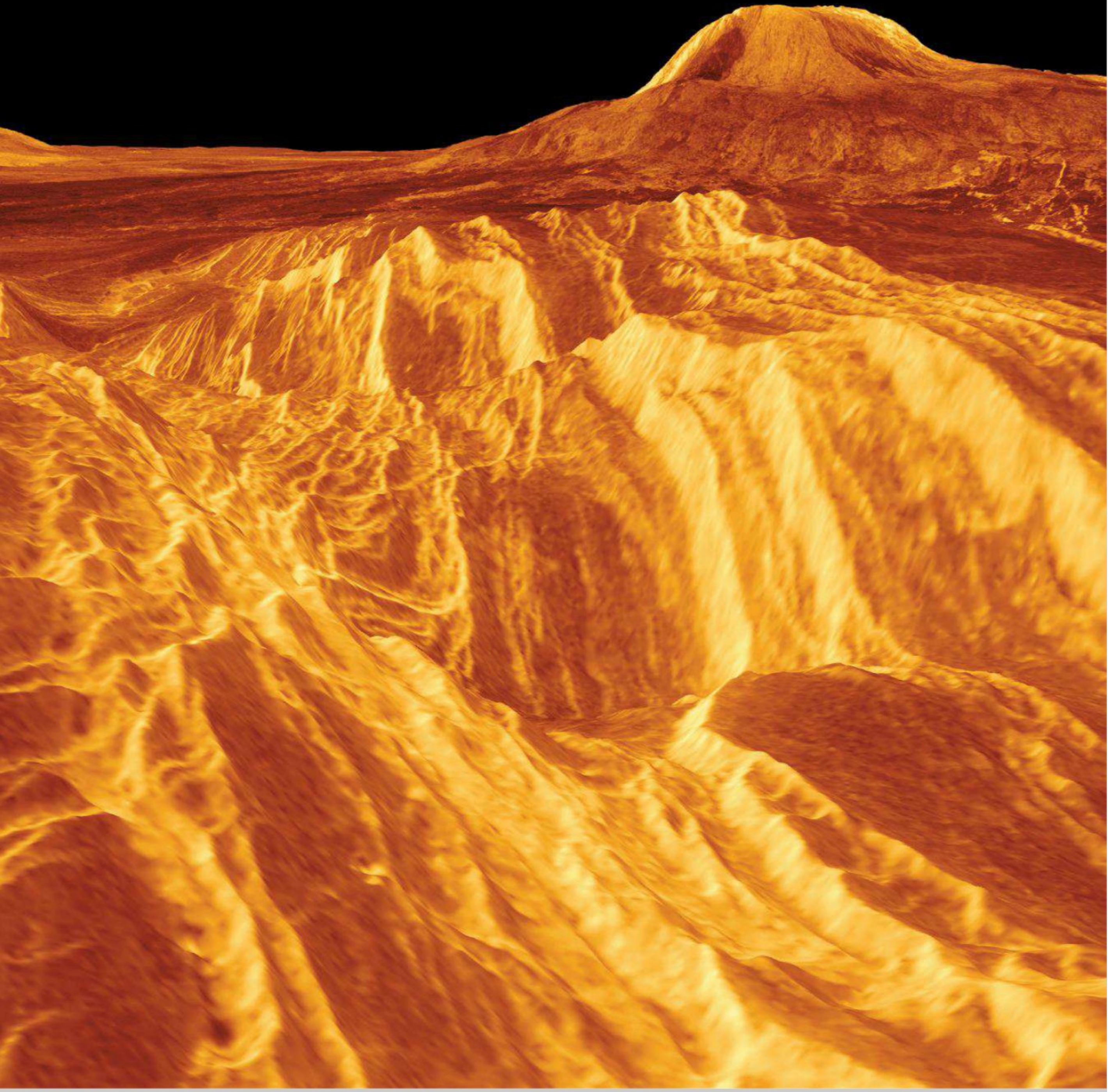
Astronomers observed other weird artifacts on the planet's surface, in addition to many substantial volcanoes

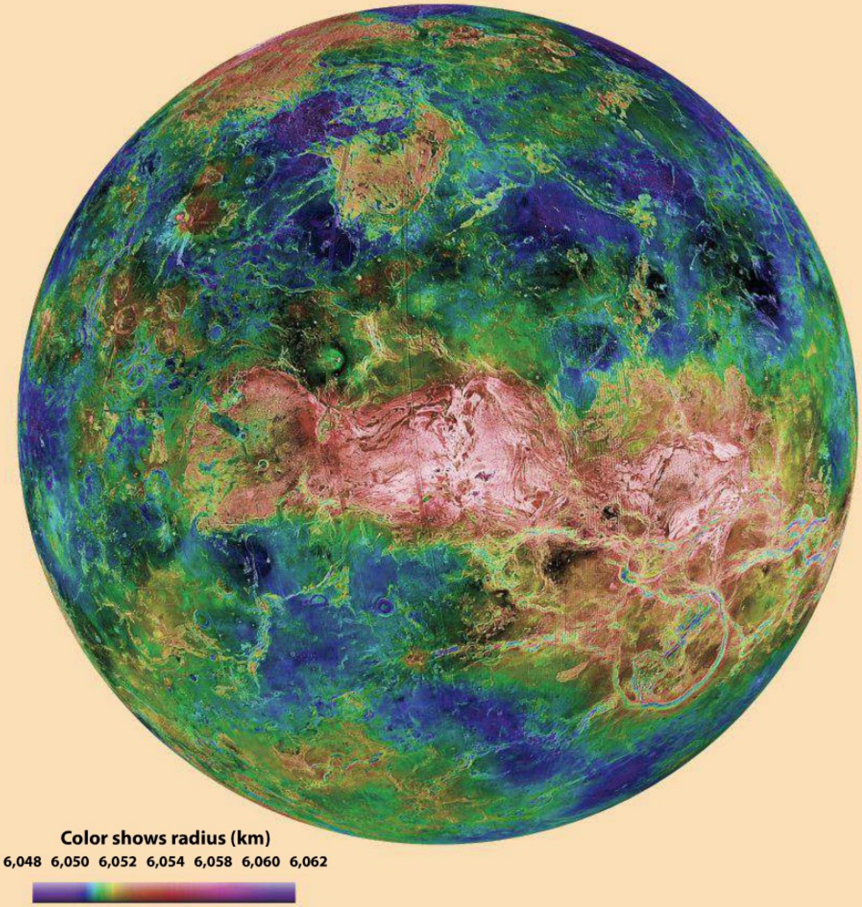


NASA/JPL

VENUSIAN 3-D. A portion of western Eistla Regio on Venus appears in this dramatic 3-D reconstruction of the terrain made using Magellan orbiter data.

NASA/JPL





HELLISH WORLD. Scientists created this hemispheric view of Venus using Magellan spacecraft data. The image is color-coded to elevation and reveals features as small as 2 miles across. NASA/JPL

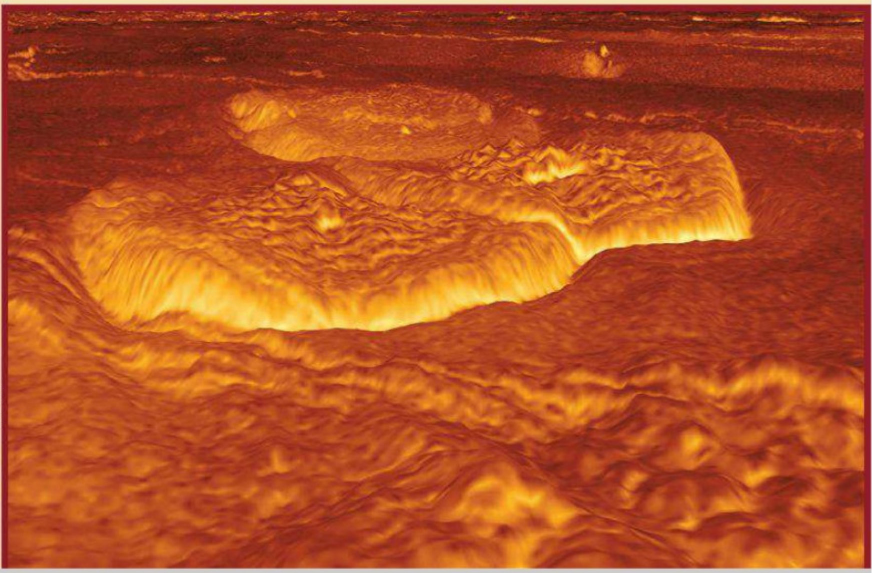
that suggest an active geology in the recent past. These include coronae (crown-shaped surface features), tesserae (crunched features where the planet's crust is pushed together and buckles), and arachnoids (circular or oval features filled with concentric rings) — so named because they are spider-like in appearance. Moreover, scientists found trace signs of erosion and tectonic shifts on our sister planet.

As scientists looked more carefully at the body of data returned from Magellan, it became clearer that this was a planet that had, somehow, turned itself inside-out. Dating various features on the planet's surface subsequently revealed Venus must have undergone a cataclysmic upheaval about 300 to 500 million years ago, very recently in geologic terms. At about that time, Venus' surface seems to have been wiped clean.

Planetary scientists believe strongly in the gradual, slow, methodical workings of nature. Venus' geology placed them in an awkward position, because a huge, catastrophic event apparently attacked the planet suddenly.

Nonetheless, in 1992, Gerald Schaber of the U.S. Geological Survey wrote that what was observed on the planet may have resulted from a "global resurfacing event or events." Don Turcotte of Cornell University followed a year later, proposing the venusian crust may have grown so thick over time that it trapped the planet's heat inside, which eventually flooded the planet with molten lava. Turcotte described the process as cyclical, suggesting that the event of several hundred million years ago may have been just one in a series.

Others have suggested that low-level volcanism may be responsible for coating the planet's surface over time without a need for any global catastrophes. But the current thinking seems to favor the huge maelstrom. "All the geologists agree," says Schaber, "Something very strange happened." Scientists have yet to determine exactly why the planet resurfaced globally and what mechanisms were involved. With the European Venus Express mission inserted into orbit in 2006, further clues will continue to roll in. ■



HILLY LAVA. Three thick dome-like hills dominate the center of this 3-D Venus image made using Magellan data. The hills, on the eastern edge of Alpha Regio, were formed by thick eruptions of lava that solidified on level ground.

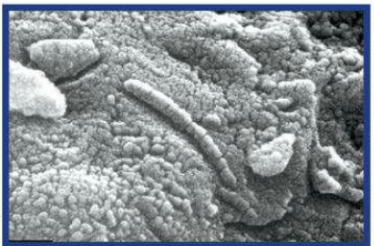
NASA/JPL

34 How could we recognize **life** elsewhere in the **cosmos?**

Living things could permeate the universe. With at least 25 thousand billion billion star systems out there, it's an incredible conceit to think Earth is the only planet in the whole universe hosting life. Yet over the history of astronomy, we know of only one planet that hosts life — ours. If we were to find life elsewhere, whether microbes in our solar system or more complex beings farther away, how would we recognize it?

It might not be easy. But there are starting points. "Astrobiologists argue some properties must be universal to life wherever it occurs," says Alan Longstaff, an astronomer and chemist at the Royal Observatory in Greenwich, England. First, life is defined as a complex chemical system that uses energy, generates waste, reproduces, and takes part in evolution over time. The successful critters on Earth, and presumably in other places too, exist in huge numbers. They also can replicate themselves successfully enough to survive the rigors of a sometimes hostile environment.

All known life is carbon-based, Longstaff reminds us. No other chemical element is as adaptive to the variety of reactions carbon can undergo. And, crucially, all life we are familiar with needs liquid water. Water allows biological molecules to interact the right way — that's why the search for life on planets in the solar system follows the mantra, "Follow the water."



NASA/JSC

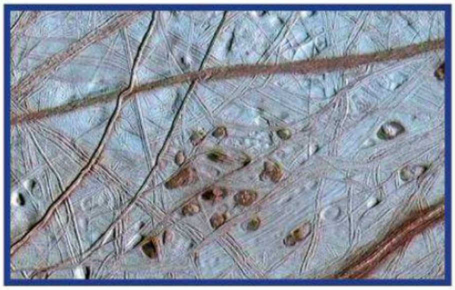
LIFE ON MARS? Arguments over life on Mars erupted in 1996 when scientists proposed that chainlike structures in a martian meteorite, ALH84001, might be fossilized microbial life. Now the consensus is the structures are chemical, not biological.

Astronomers already know of more than 200 planetary systems. Astronomers mostly can detect large "hot Jupiters" fairly close to us. As the search extends toward smaller earthlike worlds, the numbers of planets will undoubtedly rise sharply.

Even if many rocky planets are out there, how easy is it to make life? Again, the only example we have is right here on Earth. After our planet's formation 4.56 billion years ago, life left traces enriched with carbon isotopes in sedimentary rocks. The earliest yet examined, from west Greenland, date to 3.85 billion years ago. That's the earliest record of life on Earth. Considering a rain of rocks periodically battered Earth's surface, life probably started and was snuffed out several times before finally taking hold. This suggests life started quickly on Earth, and, therefore, the odds it could start elsewhere, under challenging conditions, are good.

Life can exist in hellish places — and on frozen worlds, too. In recent times, scientists have discovered hydrothermophiles that thrive in high-pressure ocean water as warm as 242° F (117° C). Many species of bacteria exist several miles underneath Earth's crust, one place that would have been safe during the heavy bombardment period. Conversely, microbial life exists in the pack ice of the Arctic and Antarctic. It, therefore, might thrive in similar conditions on Jupiter's moon Europa or Saturn's moon Enceladus.

As astronomers discover more and more exoplanets, how will they know which ones to focus on as possible habitats for life? Planetary spectra will give astronomers significant clues. Living things alter their environments through the chemical reactions they undergo while they are alive. These reactions can manifest themselves in planetary spectra as molecules that should not exist unless living creatures are producing them.

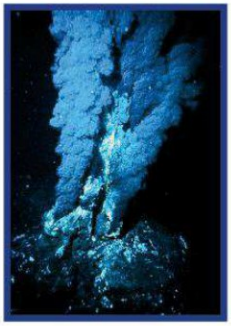


NASA/JPL

BURIED WHISPERS? Jupiter's moon Europa has an icy and cracked surface. Could microbial life exist under the ice? Recognizing it may be difficult for future space probes.

As Longstaff points out, Earth's atmosphere contains oxygen only because photosynthesis creates it faster than it is depleted by other processes, such as iron rocks oxidizing. So detecting an abundance of ozone and methane in a planet's atmosphere, for example, would be strongly suggestive of living beings on it.

But life will not be found virtually anywhere. Temperatures have to be right, and liquid water probably has to be present. Equilibrium is good: Life doesn't like wild swings in its environment. Alien life-forms, although they could be radically different than what we know on Earth, will share common characteristics and chemistry. If astronomers do succeed in detecting life elsewhere in the cosmos, one thing is certain: It will be a huge moment for the history of human civilization. ■



NOAA

BLACK SMOKER. A hydrothermal vent deep in the Atlantic Ocean shows the kind of environment where life might have first taken hold on Earth. The surprising ability to adapt to harsh environments suggests life could be plentiful in the cosmos.

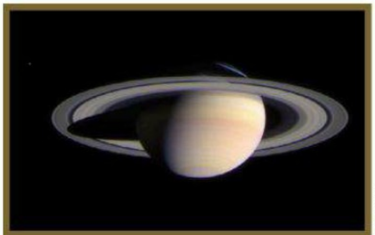
35 What created Saturn's rings?

A glance through a small telescope at the planet Saturn is often the experience that turns people on to astronomy. Simply walking outside, setting up a little scope, and enjoying a spectacular view of a distant planet, colorful and beautiful, surrounded by razor-sharp rings, is deeply satisfying. Saturn's rings were also one of the first targets of Galileo Galilei's new telescope some 400 years ago, when he revolutionized human observations of the cosmos. Among the most identifiable and familiar symbols of astronomy, Saturn's rings remain almost as mysterious today as they were to that Italian explorer. Scientists don't yet know the origin of the rings.

In 1980 and 1981, scientists got their first great view of Saturn's rings when the Voyager 1 and 2 spacecraft conducted scientific operations up close. Saturn's globe measures 74,900 miles (120,590 km) across; its rings span 300,000 miles (483,000 km).

The rings are divided into groups, designated C, B, and A, working outward from the planet. Visible in a small telescope is the black band that separates rings B and A called the Cassini Division, after Giovanni Cassini, who discovered the gap in 1675.

Astronomers continue to discover fainter rings. They are designated D (closest to the planet), F (a narrow feature just outside the A ring), and two distant rings called G and E. The early view of Saturn's rings as a continuous flat disk like a CD has changed, courtesy of the Voyagers. Today, astronomers realize the rings comprise countless thousands of particles of dirty water ice ranging from microns to meters in size.



NASA/JPL

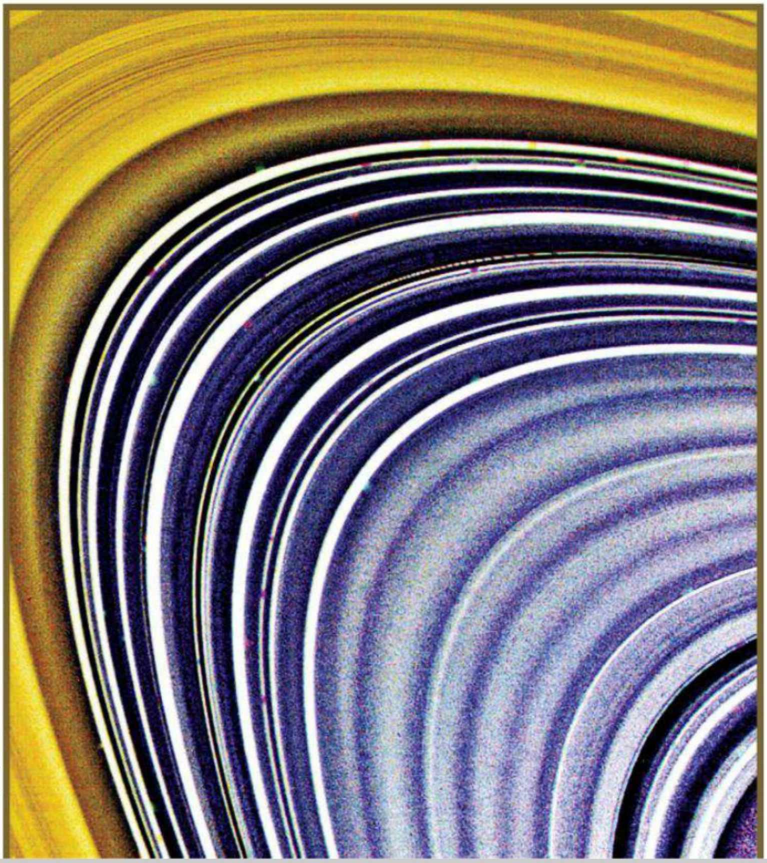
CLOSING IN. The Cassini spacecraft took this image February 9, 2004. The Sun's position (under the ring plane) causes the partial shadow on the rings.

The Voyagers found surprising structures in the rings. Unresolved ringlets and gaps might be caused by tiny satellites orbiting within the rings, astronomers reasoned.

By observing stars behind Saturn's rings, Voyager resolved objects as small as 1,000 feet (305 meters) across and showed that few gaps exist in certain rings. Instead, density waves create the effect. Some of the rings contain clumps and spokes. In the wake of the Voyagers, many unanswered questions remained.

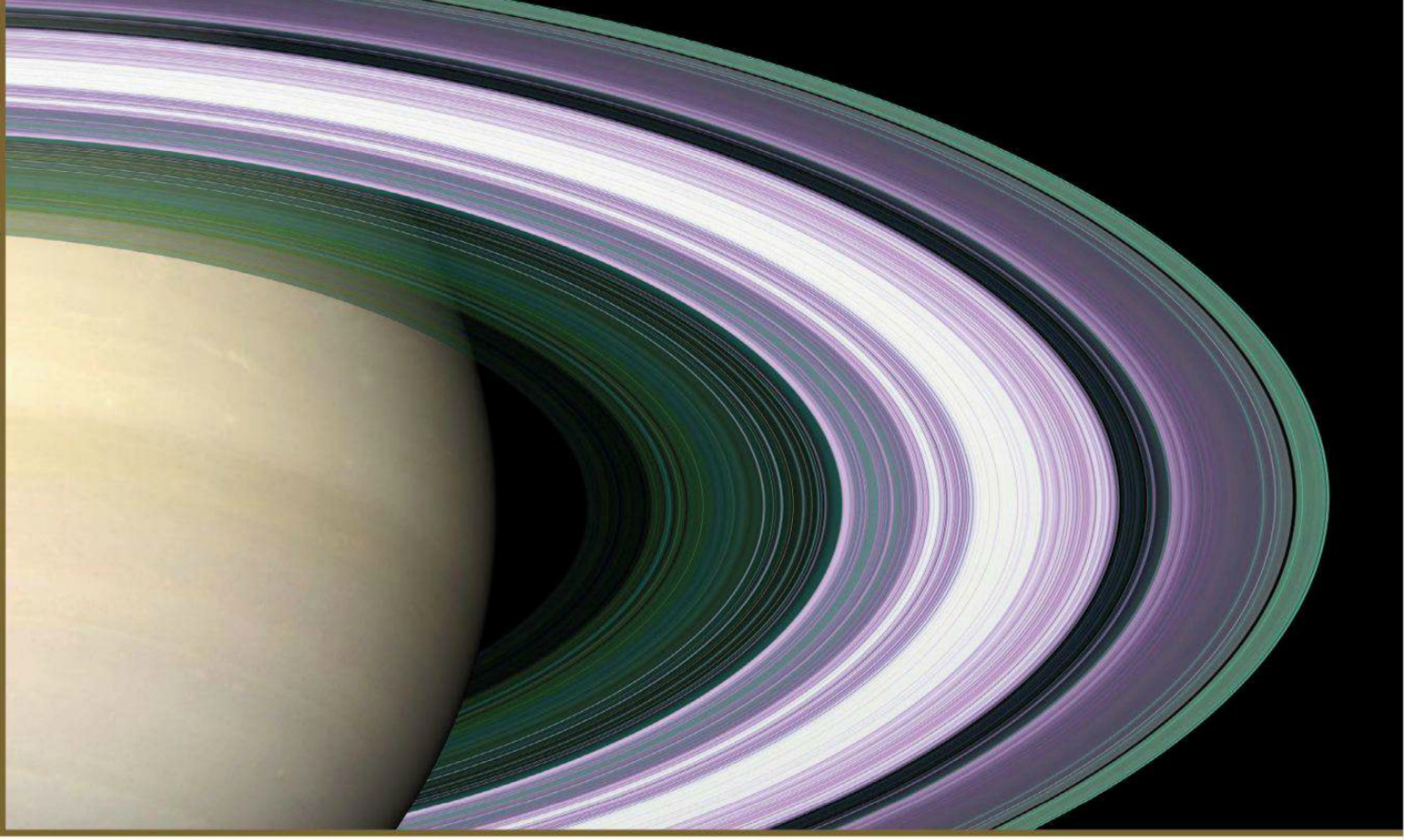
The next chapter in Saturn exploration began in 2004, when the Cassini-Huygens spacecraft entered saturnian orbit. The mission at Saturn continues; Cassini has taken a vast amount of data and produced thousands of images, and the European Huygens probe touched down on Saturn's largest moon, Titan. Careful analysis of Saturn's rings remains an ongoing project.

In April 2006, Cassini findings shed some light on the origin of the ring system. Strangely shaped gaps in some of the rings

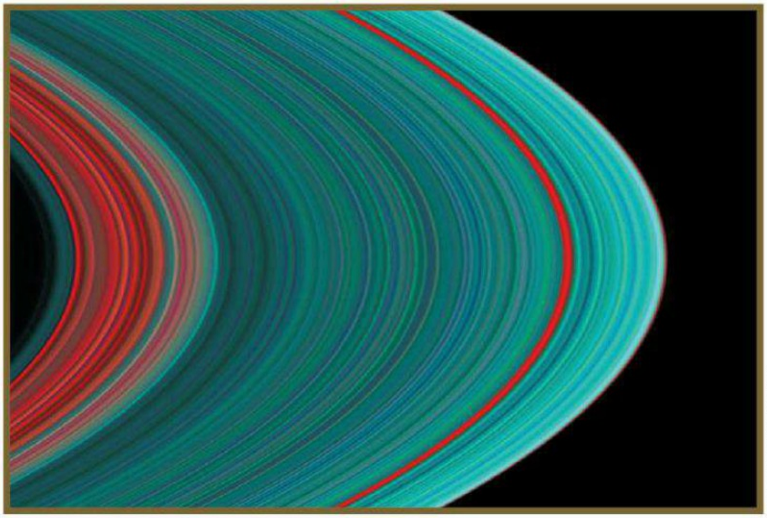


NASA/JPL

PSYCH-OUT. Saturn's C ring appears psychedelic in a false-color view shot by a camera aboard the Voyager 2 spacecraft in 1981. At the time, the spacecraft was 1.7 million miles (2.7 million km) from the planet.

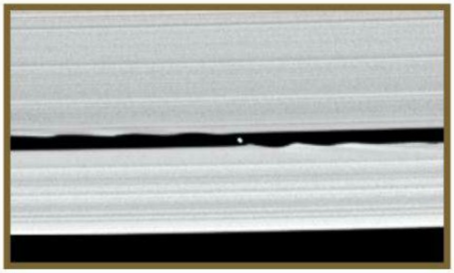


▲ RINGED PORTRAIT. **Saturn's magnificent ring system appears incredibly detailed in this image created by the Cassini spacecraft. The rings comprise particles from tiny sizes up to large boulders measuring meters across.** NASA/JPL



NASA/JPL/UNIV. OF COLORADO

◀ HOLIDAY COLORS. **Red dirt blends with green ice in this false-color, ultraviolet shot of the A ring. The Cassini Division, which is the thick red line near the right side of the image, contains lots of dirt.**



NASA/JPL

WAVY MOON. **A new moon discovered by the Cassini spacecraft May 1, 2005, orbits inside a gap in Saturn's rings and creates waves inside the rings, visible as scalloped edges.**

suggest elusive moonlets exist and support the notion that the rings are debris from an icy moon that broke up eons ago as a result of a violent collision.

The scenario may be that, about 100 million years ago, a comet or asteroid slammed into an icy moon, breaking it into pieces. Saturn's titanic gravity smoothed out the pieces into a flattened disk around the planet. The idea is not confirmed, and Cassini will continue to collect vast amounts of additional data. But, after hundreds of years, the origin of the rings is finally beginning to come into focus.

36 Could a distant, dark body end life on Earth?

Although we live in relative quiet within the cosmos, going about our lives and seeing the stars as a distant backdrop, we are very much part of the universe that surrounds us.

Dangers lurk in space, as any glance at the Moon's cratered surface confirms.

Not only must our planet avoid collisions with Earth-crossing asteroids, but more remote threats exist. If a nearby star went supernova, a gamma-ray burst erupted nearby, or a black hole or stream of antimatter somehow wandered into our neighborhood, it could spell disaster. While astronomers say those events are unlikely, another dark, distant interloper could create havoc on Earth by its mere presence.

Where could such trouble come from? The Sun hasn't always been a solitary star. It was born in a group of suns, as all stars are, and its native companions have been scattered by the gravitational tug created by orbiting the galaxy's center.

Yet some 5 billion years after the Sun's birth, a few of its associates still linger near the old neighborhood. Among them are the Sun-like star Alpha (α) Centauri, the yellowish dwarf Tau (τ) Ceti, and the cool red-dwarf Wolf 359. Is the Sun truly single, or could a cool, dark companion loom in the background, periodically nudging comets toward Earth?

> In a million and a half years, Gliese 710 will slide within a light-year of the Sun.

The discovery of Sedna, a trans-neptunian object found in 2003, and the subsequent discovery of Eris, fueled the idea that large, dark bodies float in the solar system's distant reaches. Those bodies exist apart from the numerous comets that populate the Oort Cloud. Close passages of well-known stars will occur far on down the line: For example, in less than a million and a half years, Gliese 710, a red dwarf now 60 light-years away, will slide within a light-year of the Sun. This will unleash a torrent of comets from the Oort Cloud into orbits that could intersect Earth's, and they will arrive near our planet within a liberal span of about 2 million years.

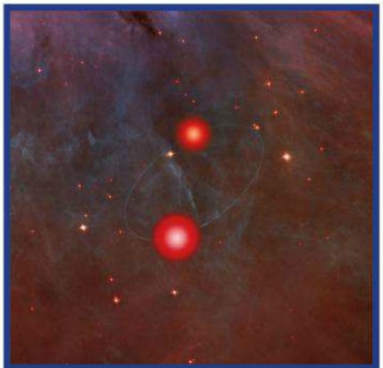
But bombings from comet nuclei could result from other sources, too. A number of astronomers suggest the Sun may have a hidden, dark companion that periodically sends comets sunward, raining them down on the inner solar system.

In 1984, University of Chicago paleontologists David Raup and J. John Sepkoski revealed their finding that Earth's extinction events were periodic. At the time, they suggested the Sun's orbit about the Milky Way's center was responsible, unleashing comets at regular intervals of about 26 million years.

In the same year, University of California at Berkeley physicist Richard Muller proposed the responsible mechanism was "Nemesis," an unseen, distant stellar companion to the Sun. Muller thought an M dwarf — a small, cool star — could lurk unnoticed in the distance yet have a huge effect on the Oort Cloud.

With the recent advent of the Two Micron All-Sky Survey (2MASS), however, astronomers scoured the whole sky at near-infrared wavelengths, producing 2 million images that would have uncovered Nemesis, had it existed. So the mystery of what lurks out in the darkness beyond the Oort Cloud, if anything, continues.

DANGER ZONE. **Many dark objects lie too far from the Sun to be observed. An unseen threat might come from deep space in the future.** *ASTRONOMY*: ROEN KELLY



UNSEEN COMPANION. A small dim object called a brown dwarf could orbit the Sun in our solar system's distant regions. Brown dwarfs fall somewhere between the smallest star and the largest planet. This artist's conception shows a pair of brown dwarfs. NASA/ESA/A. FEILD (STScI)

Not all scientists are unconcerned about the idea of a dark threat. Michael Rampino, a geologist at New York University, searches for an astronomical object he believes may be responsible for recurring extinction events every 25 to 35 million years.

As suggestive evidence, Rampino employs the large-impact events that produced craters under the Chesapeake Bay between Virginia and Maryland and in Popigai, Siberia, about 35 million years ago; and the K-T impact in the Yucatán Peninsula, the "dinosaur-killer" that occurred 65 million years ago. Rampino believes several smaller lines of evidence suggest another catastrophic impact 95 million years ago.

If a dark monster is out there, it could be a small brown dwarf. If such a starlet exists, it might weigh less than 40 Jupiter-masses, making it slip under the radar of the 2MASS survey. It would have a highly elliptical orbit that would make it hard to spot because most of its time would be spent far from us. Still, most astronomers remain skeptical. Only time will tell. 50

37 Do **we live** in a **multiple universe?**

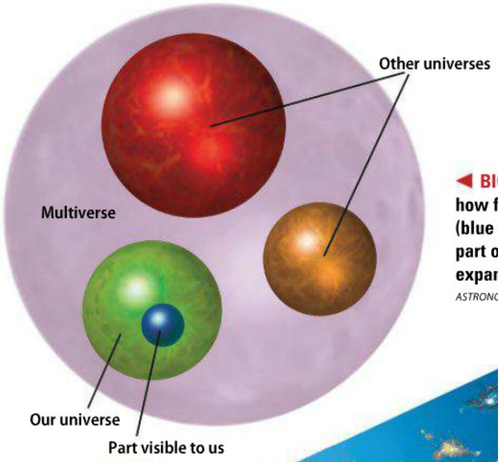
For as long as humans have gazed skyward, a question has loomed in the back of our collective mind: How do we know everything that we see is everything there is?

Decades of astrophysical research beginning in the late-19th century established the universe as we see it, culminating with the Big Bang theory. We now know the universe is about 13.7 billion years old and at least 150 billion trillion miles across. But in recent years, astronomers have begun to address a staggering possibility — the universe we can observe, and in which we live, may be one of many that makes up the cosmos.

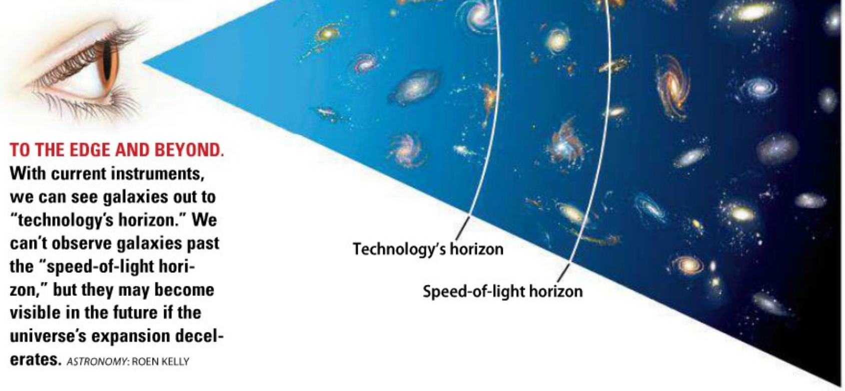
The suggestive evidence for this comes from several directions, from the idea of cosmic inflation, from string theory, and the existence of the famous cosmological constant. Some of the notions that come out of these lines of evidence are pretty counterintuitive. Yet that doesn't worry astronomers. "I fully expect the true nature of reality to be weird and counterintuitive," says cosmologist Max Tegmark of the Massachusetts Institute of Technology, "which is why I believe these crazy things."

The idea of multiple universes, or multiverses, poses the notion of the universe existing like a giant sponge. Each bubble is a distinct universe, like ours, but others could exist separated by giant voids.

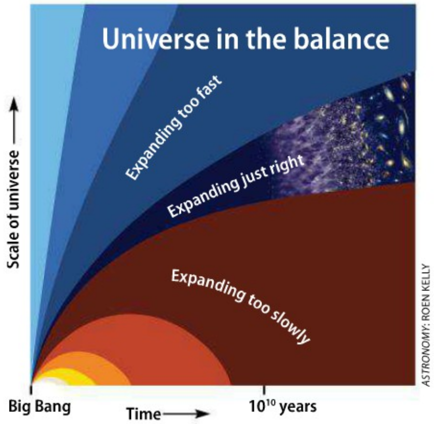
What's the evidence for all this? First, measurements of distant supernovae suggest the expansion of the cosmos is accelerating. Second, more and more evidence supports the inflationary scenario of the early history of the universe. (See "Does inflation theory govern the universe?" p. 62.) Third, ideas about inflation suggest many Big Bangs may have occurred. Fourth, recent notions about string theory suggest universes of very different types may have formed. (See "Does string theory control the universe?" p. 52.) Altogether, these notions suggest it was possible, if not probable, that



◀ BIG PICTURE. **Light's finite speed determines how far we can see, but as the visible universe (blue sphere) grows, it is an ever smaller part of a larger universe expanding even faster.** *ASTRONOMY*: ROEN KELLY



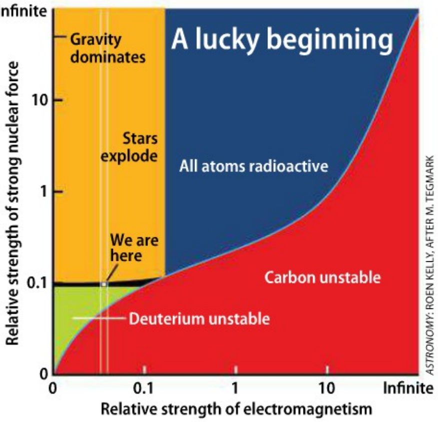
TO THE EDGE AND BEYOND. **With current instruments, we can see galaxies out to "technology's horizon." We can't observe galaxies past the "speed-of-light horizon," but they may become visible in the future if the universe's expansion decelerates.** *ASTRONOMY*: ROEN KELLY



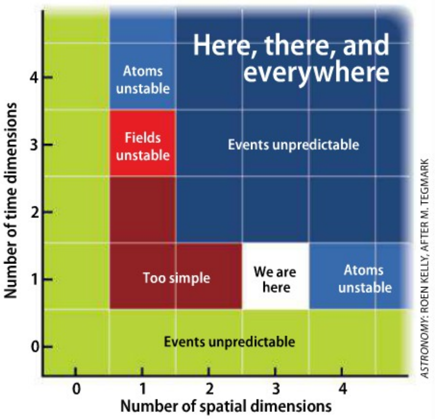
ASTRONOMY: ROEN KELLY

▲ EXPANSION RATES. **Our cosmic fate hangs on the universe getting the parameters right, or nearly so. How the universe expands, and at what rate, determines its ultimate fate.**

▼ FORTUNATE UNIVERSE. **Physical constants took on values given by chance processes when the universe was born. But if they were any different, we couldn't exist.**



ASTRONOMY: ROEN KELLY, AFTER M. TEGMARK



ASTRONOMY: ROEN KELLY, AFTER M. TEGMARK

STRANGE BREWS. Space and time might have other values in other universes, but their fates would be quite different.

multiple universes of different types formed in the past, and they coexist with the familiar cosmos we can see.

Even without other universes, astronomers know the universe is larger than what we see with our telescopes. The view horizon now spans about 14 billion light-years; and if you count the knowledge that distant objects have expanded far beyond what we now see, the "currently" existing horizon is at least 40 billion light-years across.

Accepting an inflation-based universe of the size we see, Jaume Garriga of the University of Barcelona and Alexander Vilenkin of Tufts University have proposed a cosmos peppered with numerous "O-regions," observable universes like ours. Part of the idea goes that inflation, the hyperexpansion in the early universe, never completely stopped. It stopped where we are, producing our O-region, and many others. But in other areas of the universe at large, it continues. This creates a concept called eternal inflation — a universe unlike a simple sphere, instead rather like a sponge, pocked with holes that are bubble universes.

How convincing is this to astrophysicists? Tegmark remains open. "As scientists," he says, "We're not testing the general idea of a multiverse. We're testing inflation — a mathematical theory that predicts a multiverse and all kinds of other stuff." Vilenkin looks ahead to an exciting future of learning more about multiverses. "By doing measurements in our own region," he says, "We can test our predictions for what lies beyond."

38

How did the Milky Way Galaxy form?

Taking a telescope out on a clear springtime night and scanning the area of the constellation Virgo reveals an amazing sight: Large areas of the constellation are peppered with faint smudges, the light from distant galaxies bound up in a huge swarm, the Virgo cluster. This area of sky gives us our best look at the closest large concentration of galaxies in the universe.

Astronomers have understood the basic properties of galaxies, at least that they're large congregations of stars, gas, and dust far beyond the Milky Way, since the 1920s. But really understanding galaxies, the story of their formation in the early universe and how they have evolved over the past 13 billion years, is a tricky struggle that challenges the best researchers.

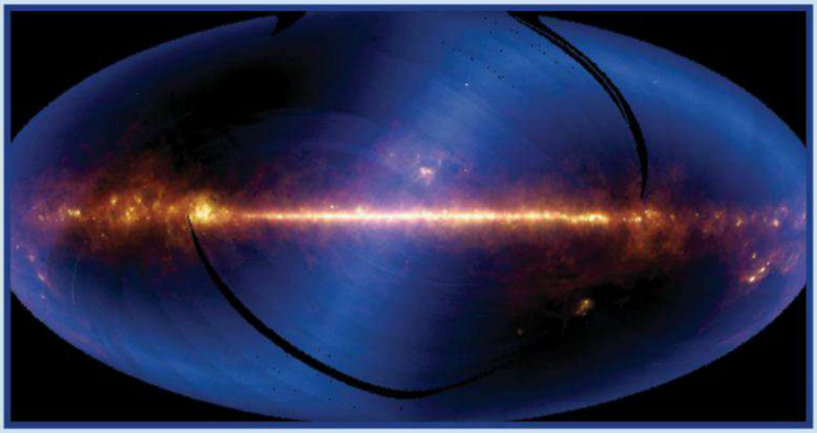
We know our own galaxy, the Milky Way, best. Astronomers have had more than a century to conduct astrophysical research on tens of thousands of objects within the galaxy. Cosmologists have made great strides over the past few decades in understanding how the universe came to be. Yet how galaxies, including our Milky Way, were born out of the early cosmos is just beginning to come into focus.

Larger and larger telescopes being used over the past few years have helped astronomers solve some questions and raise others. With the Hubble Space Telescope, for example, in its Ultra Deep Field, astronomers can see nearly back to the universe's infancy. Yet no one has seen the so-called cosmic Dark Ages, the period before stars and galaxies existed. When they do, we may see the formation of the first stars and the first

2MASS

GALACTIC KEYHOLE. The Eta Carinae Nebula (NGC 3372) contains an extremely young, hot star that is unusual in the Milky Way. Forming only 3 million years ago, it is as massive as 100 Suns.

MILKY DISK. The Milky Way's edge appears ghostly in this infrared image captured by the Infrared Astronomy Satellite (IRAS).



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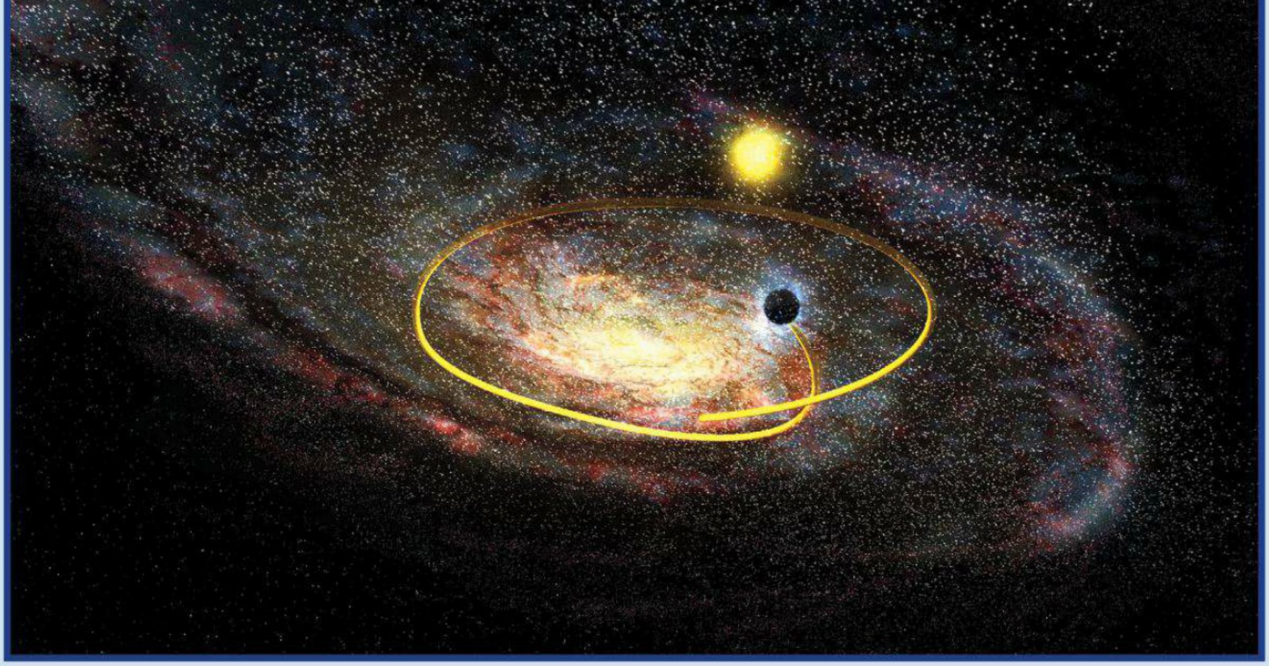

ESA/NASA/FELIX MIRABEL

SELF-PORTRAIT. **An oblique view of the Milky Way, created in an artist's impression, shows a black-hole system, GRO J1655–40, streaking through space 4 times faster than the stars in the galactic neighborhood around it.**

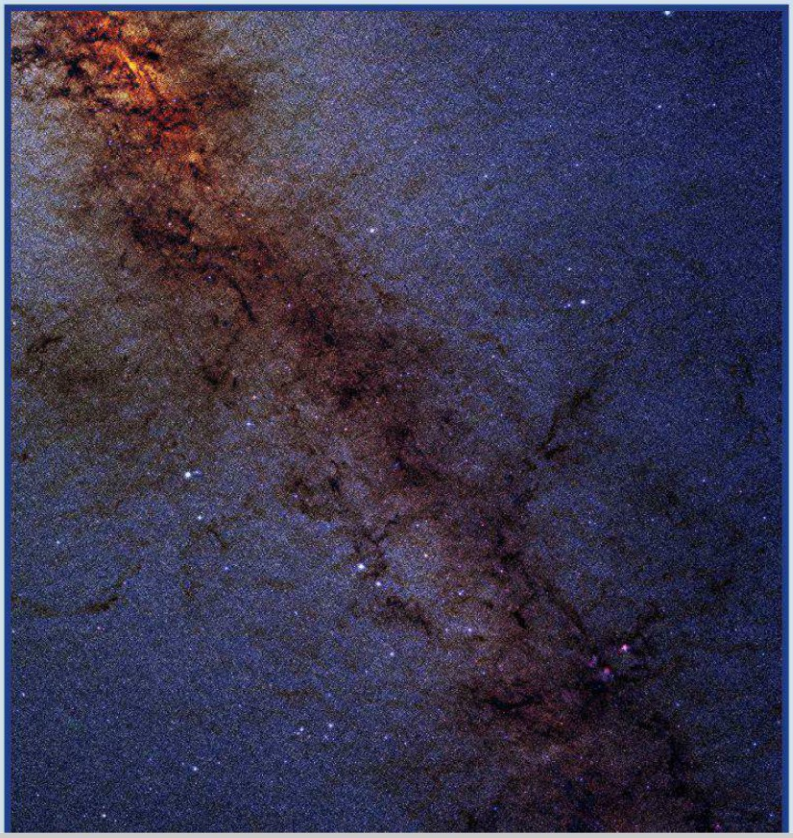
galaxies. (See "Did stars, galaxies, or black holes come first?" p. 42).

For now, astronomers have to study the numerous strange galaxies they see in exposures like the Ultra Deep Field for clues about how matter clumped in the cosmos' early days. After the Big Bang, immense heat followed, so much that matter could not form. Only a soup of subatomic particles and radiation existed.

When the universe cooled sufficiently, it became transparent to the radiation, and hydrogen atoms began to form. Ripples in the cosmic microwave background radiation — imaged by the WMAP and COBE satellites — indicate the first seeds that may have grown into black holes or galaxies. But exactly how this happened is unknown.

Many astronomers believe structures in the universe grew from many tiny pieces, the so-called bottom-up scenario. In this view, small gas clouds, star clusters, and protogalaxies merged time and time again to form ever-larger structures. Other researchers believe in the top-down model, in which huge clouds of material formed giant, sheet-like structures, such as superclusters of galaxies, that broke apart into smaller components.

For the time being, the momentum appears to be with the first scenario, because, in images of the early universe, astronomers see vast numbers of protogalaxies thought to have combined over time into normal galaxies. If this is correct, the Milky Way probably formed when star clusters came together to form the galaxy's core. As the gas clouds rotated faster, the galaxy flattened out into a disk.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GALACTIC CENTER. **The Milky Way's center, draped by thick dust clouds, stands out majestically in this infrared picture. The galaxy's core lies 25,000 light-years away and contains a supermassive black hole.**

39 How did the solar system form?

Astronomers and geologists have several techniques for dating Earth, and, therefore, the age of the solar system. From the radiometric dating of rocks, which measures the known decay rates of radioactive elements, we know Earth and the solar system are approximately 4.6 billion years old. The knowledge does not come from Earth rocks, however, the oldest of which are about 3.9 billion years old. (Earth rocks are constantly involved in vigorous erosion — by plate tectonics and volcanism — making the oldest rocks on Earth extremely hard to find.)

Instead, meteorites — chunks of asteroids, the Moon, and Mars — make dating the solar system more accurate. These bodies were left in more pristine form. The oldest radiometrically dated thus far are 4.6 billion years old, and so the solar system itself must have formed near this time.

While many ideas in astronomy have changed radically over time, the notion of how the solar system formed has changed little in the last 250 years. In 1755, German philosopher Immanuel Kant first proposed the nebular hypothesis, in which a great cloud of material, the solar nebula, preceded the Sun and planets.

In 1796, French astronomer Pierre Simon Laplace put forth a similar theory. Although he was unable to draw on supporting evidence from observations of deep space, Kant proposed the solar nebula was part of a much larger cloud of gas and dust that fell in by the weight of its own gravity and began to rotate. This gravitational contraction led to the formation of planets, both gaseous and rocky. Although the scope of knowledge about how this happened has grown considerably since Kant's time, the basic idea is the same, and it has been borne out by repeated bits of evidence.

Astronomers now know when the solar system's molecular cloud began to collapse, it measured 100 astronomical units across (1 astronomical unit is the average distance between the Sun and Earth) and had about 2 or 3 times the Sun's mass. The cloud's gravitational collapse may have commenced by the flash of a nearby supernova and the resulting pressure wave.

As the cloud fell in, several processes accelerated the collapse. The cloud's temperature rose, it began to rotate, and the rotation settled material into a relatively flat disk. The gravitational potential energy increasingly transformed into heat, and the density rose quickly.

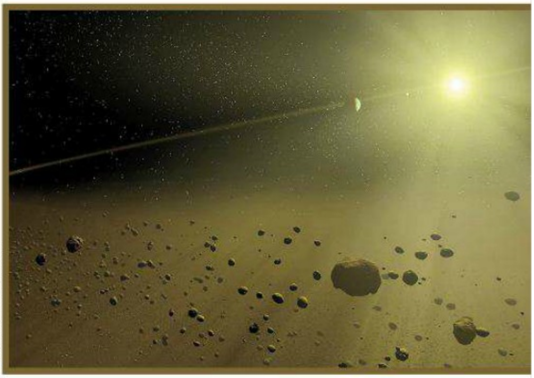
Due to the conservation of angular momentum, the flattening disk rotated more quickly as it decreased in size. As more and more pockets of gas and dust collided and stuck together, a protoplanetary disk formed, resembling a spinning pancake.

The greatest action took place at the disk's center. There, the infant protostar that became the Sun rapidly accumulated matter. After some 50 million years, the protosun gathered enough mass to commence nuclear fusion and it "turned on" as a star.

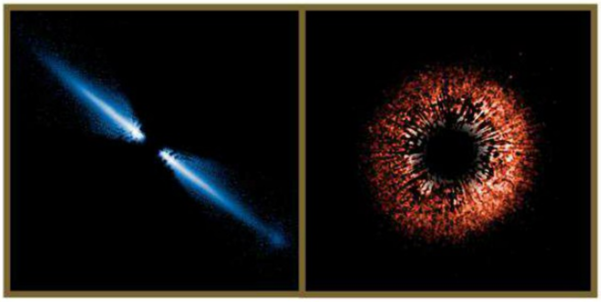
Out in the disk, meanwhile, matter continued to clump together haphazardly, making planets, thousands of minor planets, and smaller, rocky balls. After the Sun's ignition, it produced a blazing solar wind that blew minor debris and dust out of the disk. At this point, the gas-giant planets stopped accreting into larger bodies. The gas remaining in the disk, meanwhile, cooled and condensed dust (silicates and metals) and ice from the cloud. Grains of dust and ice built other planetesimals, and more and more of them stuck together to build bigger bodies.

Distant bodies in the outer solar system built up as ice worlds, and the gas giants accumulated gaseous clouds around their dense cores. Extensive sets of moons around the gas giants grew as an analog to the solar system's planets themselves. Each gas giant helped sweep the disk clean by its gravity and flung many planetesimals into the distant Oort Cloud of comets. Then, a period of heavy bombardment of numerous objects impacting the inner planets began. A giant body impacted Earth and created the Moon, and other smaller bodies became satellites, as with the moons of Mars.

The formation of the solar system offers astronomers a rare model of an early hypothesis being dead right. All the subsequent facts uncovered later in history fell right into place with Kant's original idea. ■


NASA/JPL-CALTECH/T. PYLE

ALIEN SOLAR SYSTEM. **How would our solar system appear from afar? This artist's view reveals dust and debris left from a disk of material that formed planets when the solar system was young.**


NASA/ESA

DUSTY DISKS. **Stars like our Sun, AU Microscopii (left) and HD 107146, contain dusty disks that may be planetary systems in the making. The Hubble Space Telescope imaged them in 2004.**

40

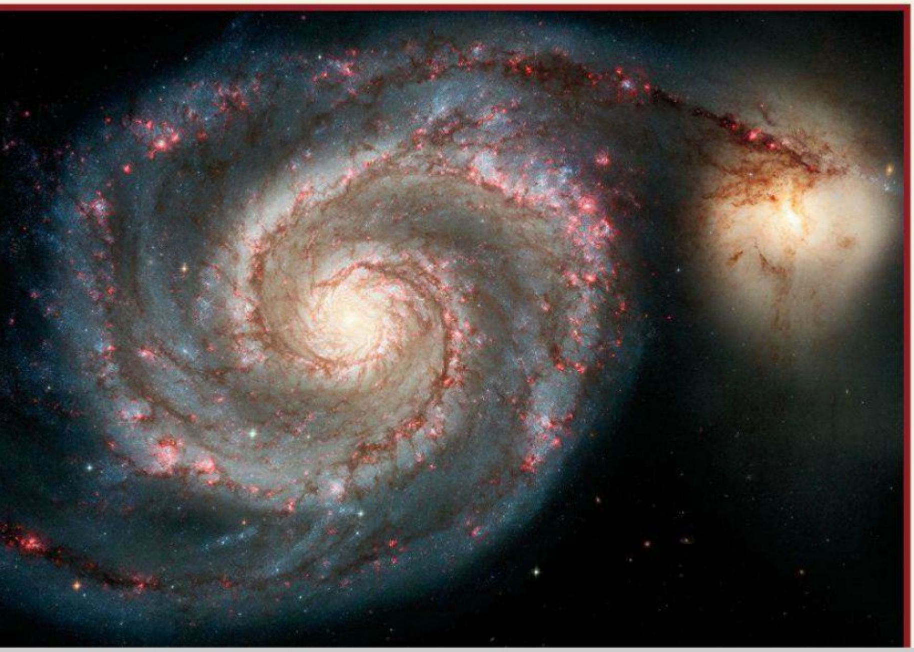
What happens when **galaxies** collide?

The vastness of space astounds us. Everywhere we look in the night sky, darkness abounds. The distances even to the nearest stars are so vast that caverns of emptiness exist between most objects in the cosmos. And the voids between the majority of galaxies are millions of times larger.

Despite the bigness of space, things do go bump in the night. Even on large cosmic scales, in galaxy clusters and groups, whole galaxies slam into each other in ornate dances that last tens of millions of years.

Even with relatively small telescopes, examples of merging galaxies are visible to backyard astronomers on Earth. In Canes Venatici, the Whirlpool Galaxy's small companion, NGC 5195, is a separate island universe passing it in the night.

Centaurus A, the great high-energy galaxy in the southern sky, is the merged debris from a head-on collision of two galaxies. NGC 4038 and NGC 4039 in Corvus, known as the "Antennae" galaxies, provide a beautiful view of two highly disrupted galaxies with an adjoined arm. In Coma Berenices, NGC 4676A and B, the "Mice," show a beautiful interaction, with a long arm shooting out one side of the merging pair of galaxies.



GALAXY KISS. **The Whirlpool Galaxy (M51) and a little interloper, NGC 5195 (top right), are colliding as the smaller galaxy whizzes past the larger one.**

NASA/ESA/S. BECKWITH (STScI)/THE HUBBLE HERITAGE TEAM

In the violent world of stars, gas, and interstellar dust, most galaxies that collide merge fully into a single chaotic object. "Minor mergers, those between a large and a small galaxy," says Yale University astronomer Daniel Christlein, "may well be a normal part of galaxy life."

In order for galaxies to merge, only two basic conditions need to be met: They must be relatively near each other, and they must be traveling at relatively slow speeds with respect to each other.

If galaxies are too far apart, their gravitational attraction would be too weak to draw them together. If they are moving too quickly relative to each other, they might pass like ships in the night.

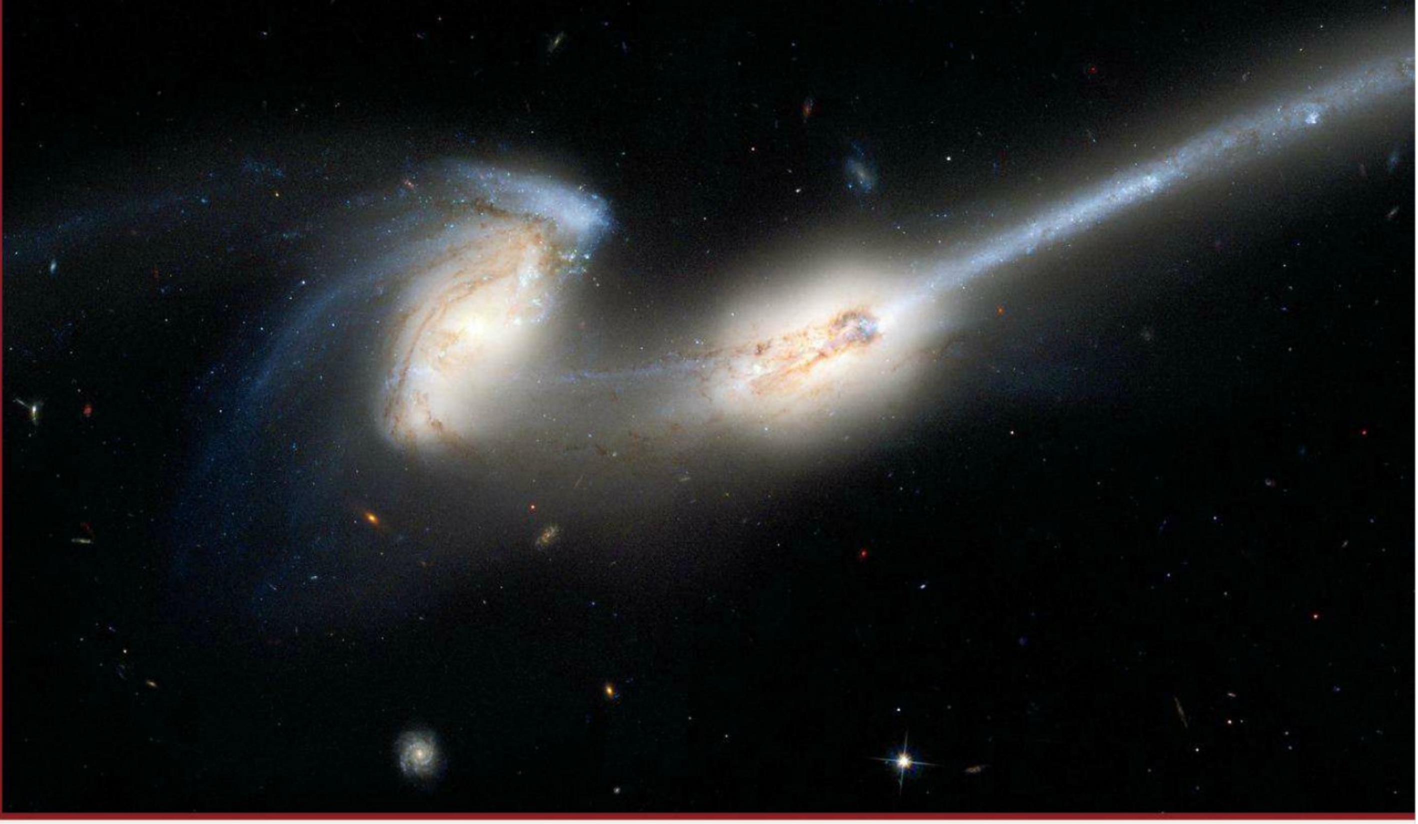
So what happens when galaxies approach? If the interaction takes place between two galaxies of different sizes, the larger object normally draws the small one into a long arc, extending it like taffy being pulled apart. The large object is relatively unaffected.

M. DONAHUE (STScI)/J. TRAUGER (JPL)

BLAZING COLLISION. **In this Hubble Space Telescope image, a dusty galaxy appears to be sliding on its edge as it passes through the larger, brighter galaxy NGC 1275 in the Perseus galaxy cluster.**

More interesting, however, are mergers between galaxies of similar sizes. Then, the fireworks start in earnest. Enormous tails of matter can be ejected; huge regions of new star formation take place as gravity compresses gas clouds; and chaotic disruption deep inside the galaxies can reorder the matter within them in wholesale fashion.

The basic building block of galaxies, hydrogen gas, is the fuel that gets twisted around in galaxy mergers. "Gas in the inner disk responds to the change in gravitational potential," says astronomer Daisuke Iono of the University of Massachusetts and the Harvard-Smithsonian Center for Astrophysics. "[It] loses energy and angular momentum, and flows toward the central regions of the galaxy. Numerical simulations predict radial gas inflow in the early stages, when



the two galaxies collided for the first time, as well as during the final coalescence."

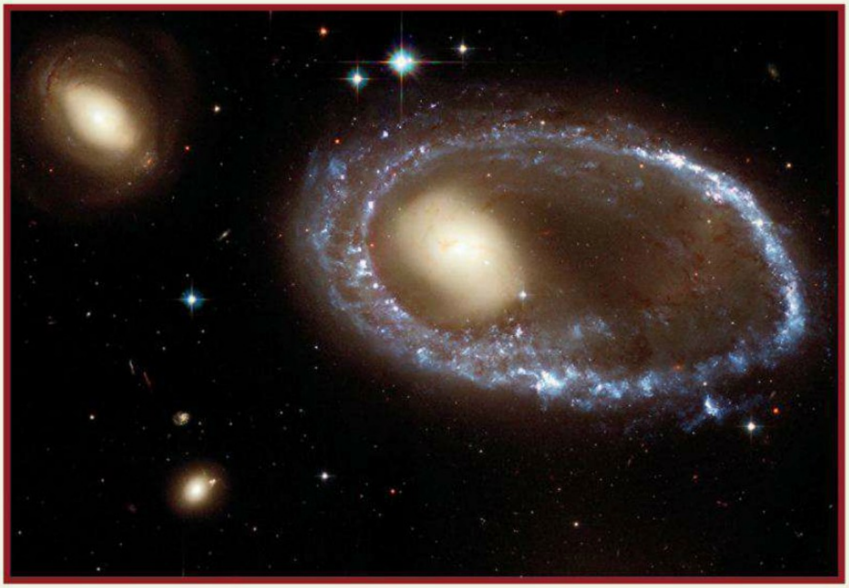
In a study of galaxy mergers conducted by Iono and his colleagues, the astronomers found the flow takes place rapidly and then slows down after more than half the gas reaches a galaxy's center. The gas then forms a ring around the galaxy's center that can trigger the bursts of star formation often seen in galaxy interactions. Dormant central black holes in galaxies can also get an injection of gas that "wakes up" the black-hole engine. This produces violent activity observed in the cores of active galaxies undergoing mergers.

The vastness of space holds true on stellar scales. The distances between stars are large enough that even as galaxies merge, their stars rarely collide. The fact that galaxies are mostly empty space holds true even as matter is compressed and galaxies, on the whole, are rocked apart. If the Sun's neighborhood of stars equaled the density of galaxies in the Local Group, our sky would be illuminated by a few stars brilliantly shining inside the orbit of Pluto!

Inside clusters and groups, galaxies collide all the time. Mergers are commonplace. Although they occur over vastly long timescales, galaxies routinely come together and become one. In fact, even our Milky Way will undergo a collision and merge with another galaxy. (See "Will the Milky Way merge with another galaxy?" on page 86.) One day, this will rock our galaxy to its core.

▲ **COSMIC TANGO. NGC 4676, a pair of galaxies known as the "Mice," dance through space as they begin merging into one giant galaxy.** STScI/G. HARTIG/THE ACS SCIENCE TEAM/ESA

▼ **TRAIN WRECK. After a head-on collision and merger of two galaxies, a ring of blue star clusters encircles the yellowish nucleus of what was a normal galaxy. The ring is larger than the Milky Way.**



J. HIGDON (CORNELL UNIVERSITY)/I. JORDAN (STScI)

41

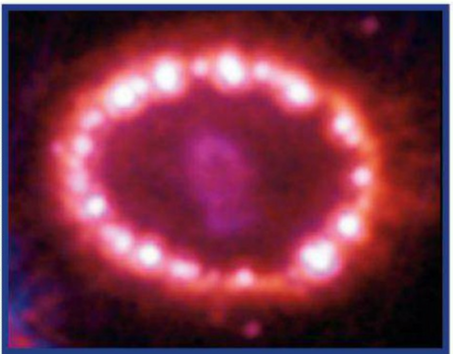
How do **massive stars explode?**

Just as people do, stars have a finite life. Born in dusty gas clouds of a galaxy's spiral arms, stars fuse hydrogen into heavier elements during their energy-producing lifetimes.

For stars, mass translates into destiny. The smallest can glow like embers for trillions of years. A middleweight star like our Sun burns steadily for 10 billion years; eventually, it puffs off its outer layers as expanding gaseous shells known as a planetary nebula. The most massive stars — furiously hot, blue-white orbs — shine brightly for a few million years and end their lives in spectacular explosions.

Supernova explosions are rare, but incredible. In a mere second, a supernova unleashes as much energy as the sum of all other stars in the observable universe. For weeks, the shattered star may rival the light output of its entire host galaxy.

The brightest recent supernova occurred in 1987 in the Large Magellanic Cloud, a satellite galaxy of the Milky Way 168,000 light-years away. The explosion, known as Supernova 1987A, left behind a remnant that's changing as astronomers watch. A shock wave traveling at 10 million mph (16 million km/h) is plowing into a ring of gas ejected before the star died. This heats knots of gas in the ring to more than 18 million degrees F (10 million degrees C) — so hot the knots emit X rays.



NASA/P. CHALLIS, R. KIRSHNER, AND B. SUGERMAN

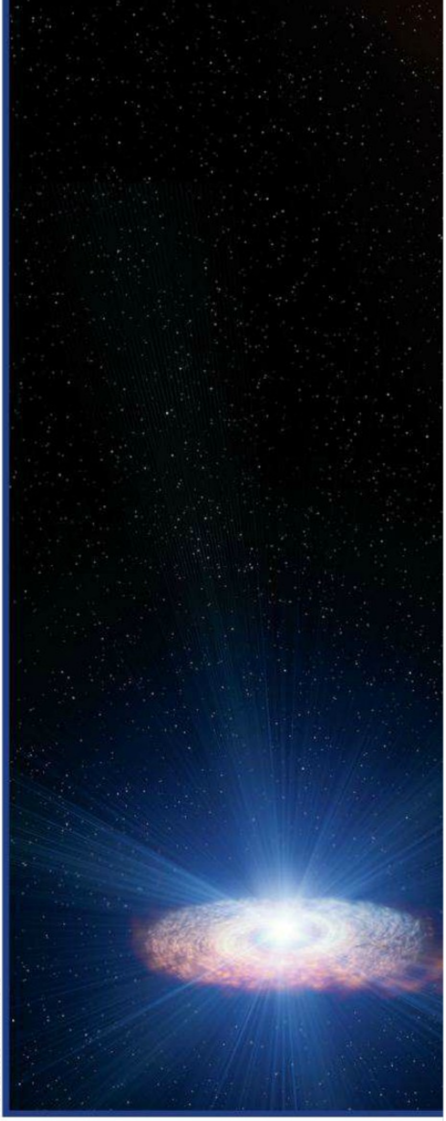
LIGHT SHOW. The blast wave from Supernova 1987A in the Large Magellanic Cloud produced a ring of bright X-ray-glowing spots, imaged in 2003. The fast-moving, ring-shaped shock wave slammed into a cloud of nearby gas at more than a million mph.

Stars fuse hydrogen and helium into heavier elements such as oxygen, carbon, and iron, but the remaining elements are forged in the heart of supernova explosions. The blasts cast these heavy elements into the universe, enriching the galaxy for the next stellar generation. Atoms in our bodies, including the iron in our blood and the calcium in our teeth, were scattered into space during the deaths of massive stars. As Carl Sagan was fond of saying, we are made of star stuff.

Supernovae are not created equal, however. In cataloging these beasts, astronomers have found significant spectral differences. The current classification scheme, devised in 1941 by American astronomer Rudolph Minkowski of California's Mt. Wilson Observatory, focuses on hydrogen, which is easy to trace.

A type I supernova is one that shows no broad absorption lines or emission lines corresponding to hydrogen. If the supernova shows hydrogen either in absorption or emission, astronomers class the exploding star as type II.

Type I supernovae are remarkably consistent; it's easy to recognize them throughout the universe. Later, some peculiarities arose. Astronomers found some type I supernovae lacking silicon, and they occasionally found others that showed the presence of helium. Scientists dubbed these rare, strange creatures types Ib and Ic supernovae and reclassified all others as type Ia.

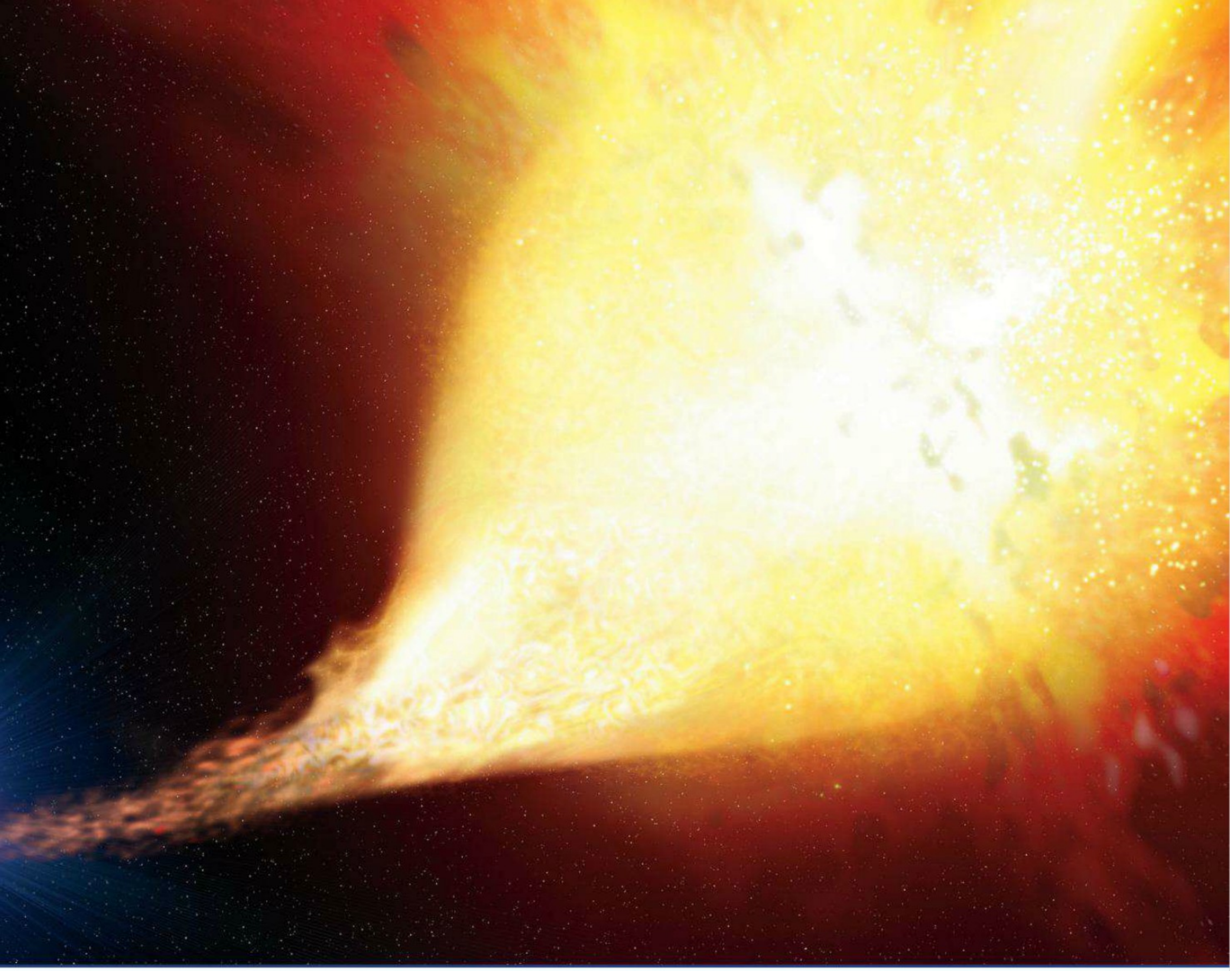


NASA/ESA/JUSTYN R. MAUND

By the 1990s, astronomers had amassed a wide enough set of observations to say with some confidence what kinds of stars are exploding.

Type Ia supernovae occur in binary systems that contain two stars of different masses that started life in close proximity.

The binary's heavier star fuses hydrogen into helium rapidly, and, once it exhausts hydrogen, it swells into a red giant and begins fusing heavier elements in its core. Ejecting its outer layers, the massive star now is a white dwarf. The star's neighbor accretes some of the shed gas. The companion's mass grows, which dramatically increases its internal temperature and the rate at which the star consumes its fuel.



DETONATION. **A white dwarf in a binary system accumulates matter from its giant companion in this illustration. The dwarf accretes matter until its own carbon ignites. The result is a type Ia supernova explosion.**

The second star swells to become a red giant. It swells so much, in fact, that its outer atmosphere extends much of the way to the white dwarf. Some of this gas now falls onto the dwarf. If the rate at which gas falls onto the dwarf is slow enough, the material accumulates on the dwarf rather than fusing. The white dwarf slowly gains mass.

As the white dwarf approaches a critical mass, its carbon heart detonates, completely destroying the star. As a result of the explosion, the dwarf's red-giant companion races off into space.

A white dwarf explodes as it edges toward a critical mass.

Supernova 1987A was a type II supernova. It began life as a star more than 8 times the Sun's mass, which glows blue-white. As the star exhausts its hydrogen fuel, it fuses ever-heavier elements, ultimately leaving an iron core surrounded by silicon, oxygen, carbon, and helium shells.

But iron fusion requires more energy than it gives, and the star's iron core collapses. At densities exceeding that of an atomic nucleus, the inner core stiffens, rebounds, and expands outward against the still-collapsing star. This makes a violent shock that shatters the star, but the details still elude astronomers.

Without supernovae, the heaviest elements forged inside stars would never be scattered into space. Type Ia supernovae show such little variation in their energy outputs that they've become important tools for exploring the distant cosmos. Study of these explosions reveals the universe's expansion is accelerating. SD

STELLAR CORPSE. After the Sun's death, much of its matter will dissipate as a planetary nebula, a slowly expanding bubble of gas. The Helix Nebula in Aquarius represents one of the sky's most beautiful such objects. NASA/ESA/C. R. O'DELL, M. MEIXNER, AND P. McCULLOUGH

42

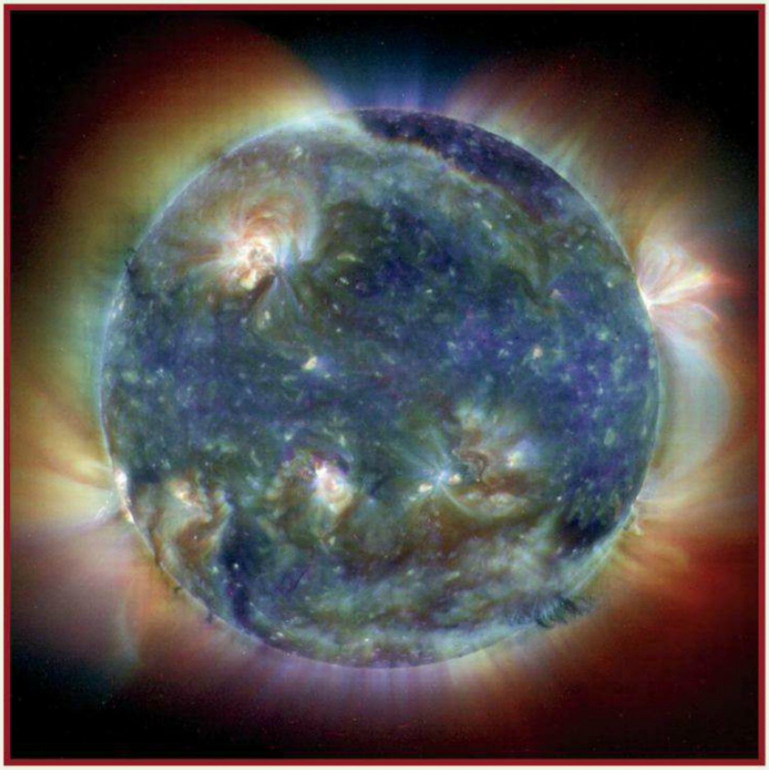
What will **happen** to the **Sun**?

The Sun is an ordinary star. It bathes the solar system with light and heat, making life possible on Earth. It's as regular as clockwork, and it sets our daily life cycles in conjunction with Earth's spin. Little wonder ancient peoples revered the Sun as a god. Yet the Sun will not always be steady and reliable. Billions of years from now, the Sun's finale will turn Earth — and the entire inner solar system — into a very nasty place.

At 4.6 billion years old, the Sun is about halfway through its life. Its adulthood, called the main sequence phase, lasts 10 billion years. When the Sun runs out of hydrogen fuel, it must generate energy by fusing heavier elements.

At that point, its main sequence phase is over. In one of the most peculiar transformations we know of, the Sun's helium core, about the size of a giant planet, will contract and heat up. And, in response, the Sun will expand by 100 times.

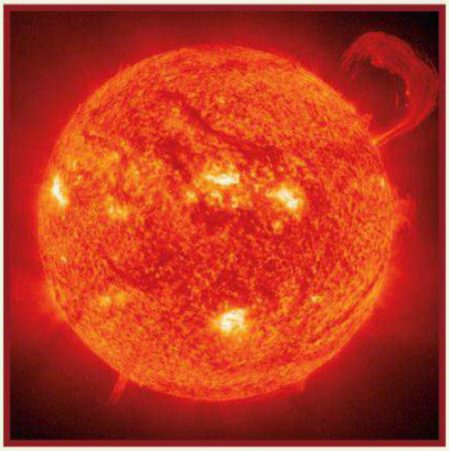
The swollen Sun will consume the planets Mercury and Venus — and possibly Earth as well. Astronomers watching from another solar system would classify this bloated version of our Sun as a red giant.



NASA/ESA/SOHO

◀ **SOLAR PORTRAIT. An image of the Sun from the NASA/ESA Solar and Heliospheric Observatory (SOHO) reveals complex features visible uniquely at each wavelength.**

▼ **BIG STORM. An enormous, handle-shaped prominence juts from the Sun's disk in this September 14, 1999, SOHO image. Prominences are huge clouds of cool, dense plasma suspended in the Sun's outermost atmosphere.**



NASA/ESA/SOHO

The Sun will consume Mercury and Venus — and maybe Earth, too.

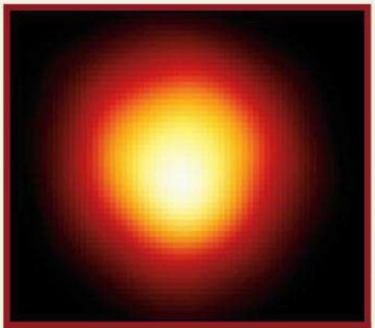
With the Sun's transformation into a red giant come new types of fusion reactions. An outer shell will fuse hydrogen as the byproducts fall inward, further compressing and heating the core. When the core reaches 180 million degrees F (100 million degrees C), its helium will ignite and begin to fuse into carbon and oxygen.

The Sun will shrink somewhat, but, after a time, and for 100 million years, it will again expand. It will then brighten significantly as it plunges toward the end of its helium-burning phase, when vigorous outflows called stellar winds strip the Sun's outer layers. This will lead to the Sun's final life phase — a cyclical, gentle shedding of gas into what astronomers call a planetary nebula.

As the swollen Sun incinerates the solar system's inner planets, its outer, icy worlds will melt and transform into oases of water for tens or hundreds of millions of years. "Our solar system will then harbor not one world with surface oceans," says astronomer S. Alan Stern of the Southwest Research Institute in Boulder, Colorado, "but hundreds — all the icy moons of the gas giants, as well as the icy dwarf planets of the Kuiper Belt." Pluto's temperature, says Stern, will resemble that of Miami Beach.

A question Stern and other planetary scientists are asking: Will the outer worlds with newfound water evolve life in the relatively brief intervals they have to do so? The liquid water on these worlds might exist for only a few hundred million years. After that, the Sun's luminosity will dim to the point where these new water worlds will permanently refreeze. Hydrocarbons that could contribute to life's emergence are already there, though. So, it's possible that, in its death throes, our Sun may seed new life.

Some 10 billion red giants blaze today in the Milky Way Galaxy. Among all of these aged stars, might some have spawned new life on worlds that remained frozen during the stars' main sequence phases? It's possible, say astronomers, but only time — and a whole lot more research — will tell. SD

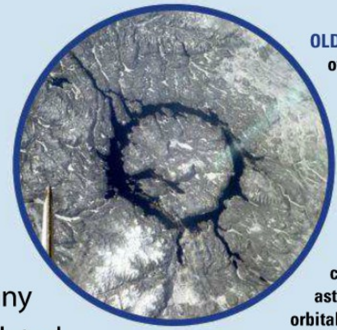


NASA/ESA/ANDREA DUPREE AND RONALD GILLILAND

MASSIVE OLD GIANT. In 1996, the Hubble Space Telescope captured the first direct image of a star's disk. The star, Betelgeuse, a red supergiant, is one of the brightest in the constellation Orion. Five billion years from now, our Sun will become a red giant.

43

Did **comets** bring **life** to **Earth?**



OLD WOUND. Evidence of ancient impacts still scar Earth's surface. Quebec's Manicouagan Reservoir, some 60 miles (96 kilometers) across, marks the site of an ancient impact crater. Space shuttle astronauts took this orbital image in 1983. NASA

Understanding how life began on Earth engages many fields of science. It's a complex question involving related bits of physics, chemistry, astronomy, and biology. Things have come a long way since the fourth century B.C., when Aristotle taught that life arose on its own from inanimate objects.

Critical findings of the past 5 decades all point to a picture of how complex, self-replicating cells could have commenced in Earth's early days. In the 1950s, chemists Harold Urey and Stanley Miller demonstrated that small, life-related molecules, such as amino acids, could have formed under conditions likely present on the young Earth.

Phospholipids, components of biological membranes, form cell-like structures spontaneously. Chemical compounds called nucleotides, linked up during chemical reactions, could have formed self-replicating RNA molecules.

The ribosomes in cells, where RNA translates genetic code into proteins, could have formed out of precursor molecules and begun to synthesize proteins. And proteins themselves would likely have become dominant life-related large molecules, leaving RNA and other nucleic acids to carry genetic "blueprints" down subsequent generations.

Complex organic molecules exist on asteroids, and probably comets.

Based on the realization that life could get going on early Earth despite hostile conditions, scientists have developed several theories about how it first emerged. One idea is the so-called RNA world hypothesis. This suggests that RNA molecules could have formed spontaneously and catalyzed their own replication.

So-called metabolism-first models come next. These ideas suggest a primitive metabolism arose and led to the development of RNA. The so-called bubble theory suggests organic molecules concentrated on ocean shores just as bubbles concentrate in breaking waves. When enough prebiotic material came together to form the right chemical reactions, the development of living systems began.

Other models include physicist Thomas Gold's "deep-hot biosphere," which posits that biomolecules formed several miles below Earth's surface.

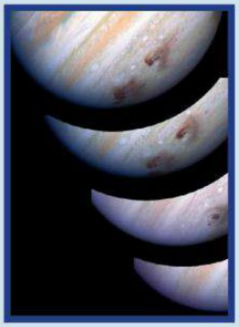
Some suggest comets may have delivered Earth's organic materials. In the solar system's early days, Earth underwent a period of heavy bombardment. Hundreds of thousands of small bodies crashed into the planets and their moons. Vast numbers of comets and asteroids struck Earth, and they left behind incredible amounts of water. In fact, impacts may have delivered much of the water now contained in Earth's oceans.

But comets likely left other important chemicals behind. Complex organic molecules like amino acids exist on asteroids, and probably on comets, too. The Murchison meteorite, a carbonaceous chondrite that fell in Australia in 1969, contained two types of amino acids. Impacting comets could have deposited these protein building blocks, crucial for living organisms, into Earth's oceans before complex cells developed.

Experiments show complex organic molecules can survive the crash of a comet or asteroid. How significant were cometary contributions in seeding the young Earth with organic chemicals? No one knows.

BRINGER OF LIFE? In May 2004, Comet C/2001 Q4 (NEAT) blazed across the night sky. In the early history of the solar system, comet collisions may have brought a great deal of water to Earth — and perhaps the building blocks of life, too.

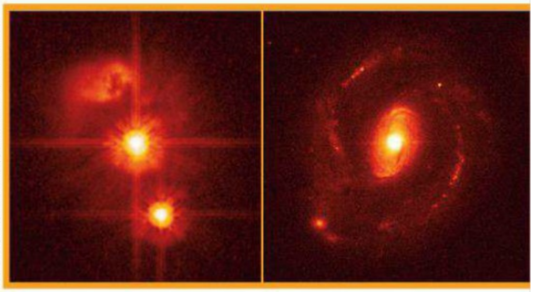
WIYN/NOAO/AURA/NSF/T. A. RECTOR, Z. LEVAY, L. FRATTARE



SHOOTING GALLERY? In 1994, fragments of Comet Shoemaker-Levy 9 slammed into Jupiter. The impacts created brownish, Earth-sized dust clouds in the planet's atmosphere. NASA/R. EVANS, J. TRAUGER, H. HAMMEL, AND THE HST COMET SCIENCE TEAM

NASA/ESA

DEEP VIEW. **Galaxy NGC 4319 and quasar Markarian 205 (top right) make an odd couple. NGC 4319 is 80 million light-years from Earth, but the quasar is a billion light-years away.**



NASA/ESA/ESO/FRÉDÉRIC COURBIN AND PIERRE MAGAIN

YOUNG GUNS. **Quasars are energetic galaxy cores. The double quasar at left is 5 billion light-years away. The one at right, just 1.5 billion light-years away, clearly lies within a galaxy.**

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How did quasars form?

Quasars, short for quasi-stellar objects, were first identified in 1962 by Maarten Schmidt at the California Institute of Technology. They appear as star-like points, but they lie at enormous distances, which means they're emitting incredible amounts of energy.

By the 1980s, quasars' prodigious X-ray and radio emissions led most astronomers to believe these objects contain black holes in their centers. In the 1990s, scientists increasingly viewed quasars as young galactic cores where gas, dust, and stars fed a central black hole.

One byproduct of the infalling matter is a high-energy jet erupting from near the black hole and hurling material into space. Quasars became part of a spectrum of energetic galaxies called active galactic nuclei (AGN), which also includes Seyfert galaxies, BL Lacertae objects, and radio galaxies. Perhaps these diverse objects, astronomers thought, were similar creatures viewed from different angles.

Slowly, the question of what quasars are morphed into how quasars formed. Observational clues from the Hubble Space Telescope and other instruments able to observe the far reaches of the cosmos are giving astronomers leads. Some quasars seen at high resolution exhibit a "fuzz" of light. In recent years, Hubble has revealed faint galactic forms around quasars. This confirms these distant beacons are, indeed, young galactic cores.

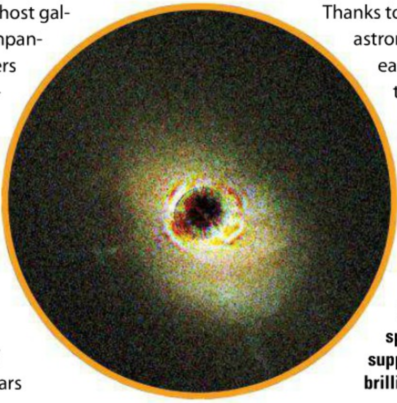
Some quasars observed in the 1990s appeared "naked" — they seemed to have no host galaxy. But subsequent research with better instruments revealed fuzz around many of these objects, too.

Another striking discovery came with Hubble observations showing more than a third of quasar host galaxies have a small companion. Perhaps encounters between galaxies trigger activity by sending extra fuel toward the central black hole.

For years, quasars provided the only way astronomers could get a glimpse of the early cosmos. Astronomers' assumption that quasars were linked to the formation of galaxies was key to understanding how everything in the early universe formed. They've confirmed that quasars are young, energetic galaxies. And supermassive black holes appear to be typical in all but the smallest galaxies — including our own.

Many nearby galaxies have dormant black holes that are now noticeable only by their gravitational effects on nearby objects. In the Milky Way, the motions of stars near the galactic center reveal the presence of an invisible object several million times the Sun's mass. Studies of the giant elliptical galaxy M87 betray the presence of a 5-billion-solar-mass object.

Since their discovery, quasars' distant beacons have shone a guiding light on some of cosmology's biggest questions. They promise to give astronomers additional answers, too — especially with the help of Hubble and its descendants. Thanks to far-flung quasars, astronomers' view of the early universe will continue to improve.



INSIDE VIEW. **The nearby quasar 3C 273 glows brightly enough to be observed with backyard telescopes. Astronomers imaged its host galaxy using a special technique that suppresses the quasar's brilliance.** NASA/J. BAHCALL

INCOMING. Some 3 billion years from now, the Andromeda Galaxy (M31), the closest large spiral to the Milky Way, will drift close enough to begin merging with our home galaxy.

45 Will the **Milky Way** merge with

Galaxies in groups and clusters frequently pass close to each other. They sometimes collide and merge in spectacular fashion. The Milky Way is a dominant member of a tribe of galaxies called the Local Group. Astronomers recognize about three dozen members, most of which are quite small. Although there's a great deal of space between the galaxies in the Local Group, the question arises: Will the Milky Way merge with another galaxy?

In fact, our galaxy formed from past mergers, and it will be the scene of many to come. The likeliest scenario of galaxy formation and evolution suggests that galaxies grew in the early universe by merging with many small protogalaxies. Scientists think our galaxy grew during its first few billion years by shredding and cannibalizing as many as 100 small protogalaxies.

But the galaxy's merger-mania continues. Astronomers see evidence the Milky Way has gobbled up as few as five and perhaps as many as 11 small galaxies in the past few hundred million years. These mergers don't result in the massive bursts of star formation astronomers observe when two large galaxies come together. (See "What happens when galaxies collide?" p. 78.) Instead, these mergers occur as the Milky Way rips apart and slowly absorbs small dwarf galaxies that have strayed too close.

How do astronomers know about the Milky Way's ancient galaxy mergers? The evidence lies scattered in the record of globular star clusters and old stars orbiting in the galaxy's halo, which extends high above and below its disk.

Astronomer Dougal Mackey at England's University of Cambridge studied these objects. He found that older clusters are remnants from the Milky Way's formation. Younger ones, however, may be imports carried into the Milky Way from dwarf galaxies it has absorbed. Cataloging these objects, their positions, velocities, and nature can help astronomers reconstruct our galaxy's merger history.

TONY AND DAPHNE HALLAS

YOU-HUA CHU AND YAËL NAZÉ

▲ **CLOUDY LUNCH. Bursts of star formation explode in N11B, a cloud of gas and dust in the Large Magellanic Cloud (LMC), a satellite galaxy to the Milky Way. Although it lies 160,000 light-years away, the LMC will be drawn in and "eaten" by the Milky Way over time.**

another **galaxy**?

One merger is under way now. A small dwarf galaxy called the Sagittarius Dwarf Spheroidal galaxy is being torn apart and absorbed by the Milky Way. The galaxy lies in Sagittarius, and a stream of stars, gas, and debris over other parts of the sky show it is being shredded. Along with astronomer Gerry Gilmore, Mackey suspects the Milky Way may have experienced seven recent mergers with dwarf galaxies like this one.

"A handful of mergers is not inconsistent with the remnants that we see," Mackey says. "In my opinion, there's no doubt more remnants are to be discovered yet, probably in the form of stellar streams like those observed from Sagittarius."

Eating dwarf spheroidal galaxies is one thing. Major mergers are far more explosive, far more traumatic. The Milky Way is due for one several billion years from now with none other than the most famous galaxy in the sky, the Andromeda Galaxy (M31). This largest member of the Local Group, a favorite of backyard observers, is moving toward us at 216,000 mph (348,000 km/h). At this speed, 3 to 4 billion years from now, the two giant spirals will begin to merge. The result may resemble the Antennae or Mice galaxies we now see locked in embrace.

"It's quite likely to be a rather messy affair," says Mackey of the future encounter with Andromeda. "The gravitational forces between the two galaxies will distort and disrupt them both, sending vast plumes of stars out into intergalactic space, never to return. The first close pass will excite tidal tails, and will also probably result in a 'bridge' of stars between the Milky Way and Andromeda," he predicts.

"After the first close pass, the galaxies will move apart and then fall back together a second time, sending out more stellar streams and further disrupting each galaxy," Mackey explains. "This cycle will occur several additional times, producing ever more complex patterns of ejected stars."

The interaction hurls stars, dust clouds, gas, and planets into space, but each pass brings the two distorted galaxies closer. "Eventually, the densest regions of the two galaxies will merge, surrounded by a complicated mixed halo of stars," Mackey says.

Those will be exciting times for inhabitants of the Milky Way. ■

46

How many brown dwarfs exist?

In 1975, Jill Tarter, then at NASA's Ames Research Center, coined the term "brown dwarf." Before that time, astronomers hypothesized the existence of so-called black dwarfs, dark objects that were free-floating and lacked the mass to "turn on" as stars. Back then, ideas about low-mass, star-like objects suggested those with masses less than 9 percent of the Sun's wouldn't undergo normal stellar evolution. Instead, they would become "stellar degenerates" heavily laden with dust and characterized by cool outer atmospheres.

Various ideas about star formation suggested there should be many brown dwarfs in the galaxy. But being nearly dark, they'd be hard to find. The best strategy would be to look in the infrared part of the spectrum.

Lack of success in identifying brown dwarfs, which certainly should have existed, stymied astronomers. They turned to various methods in vain attempts to find them. These included careful imaging around main-sequence stars and white dwarfs, hoping to find companion brown dwarfs; surveys of young open star clusters, in which brown dwarfs could be floating freely; stellar radial-velocity measurements; and multiwavelength imaging surveys.

The result? Nothing.

> The Milky Way may hold as many brown dwarfs as normal stars.

Then, in 1988, Eric Becklin and Ben Zuckerman of the University of California at Los Angeles identified a faint companion object to a white-dwarf star designated GD 165.

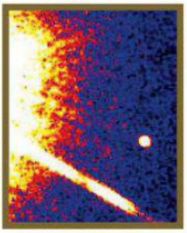
GD 165B exhibited an unusually red spectrum. Astronomers classed it as the first L-type dwarf, an extremely low-mass object. The star's spectral signature showed characteristics Becklin and Zuckerman expected from a red dwarf, but with significant differences. Suddenly, astronomers had a leading brown-dwarf candidate.

In 1995, astronomers found three more. One, Gliese 229B, has a temperature and luminosity well below that of the coolest star. It is now the prototype of a class of still cooler objects called T dwarfs. With discoveries of many objects like Gliese 229B, one of the most nagging mysteries found resolution in the 1990s.

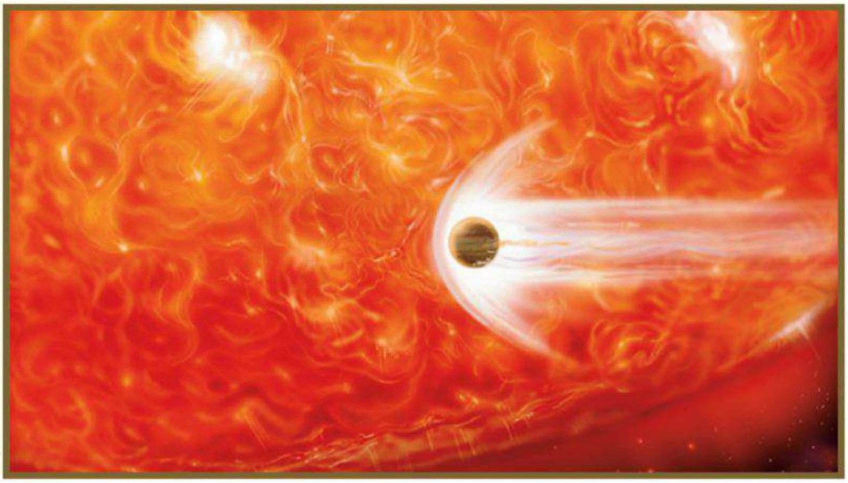
Classifying such objects is tricky, however. When brown dwarfs are young, it's extraordinarily difficult to distinguish them from very-low-mass stars. The best test is to measure the amount of lithium in the object's spectrum. Stars fuse lithium over their first 100 million years or so, but brown dwarfs cannot, so they show significantly more lithium in their spectra.

But the galaxy's true brown-dwarf population remained ambiguous until the 2MASS All-Sky Survey, begun in 1997. Conducted at a wavelength of two micrometers, 2MASS revolutionized the search. Quickly thereafter, J. Davy Kirkpatrick of the California Institute of Technology and other astronomers found many objects like GD165B.

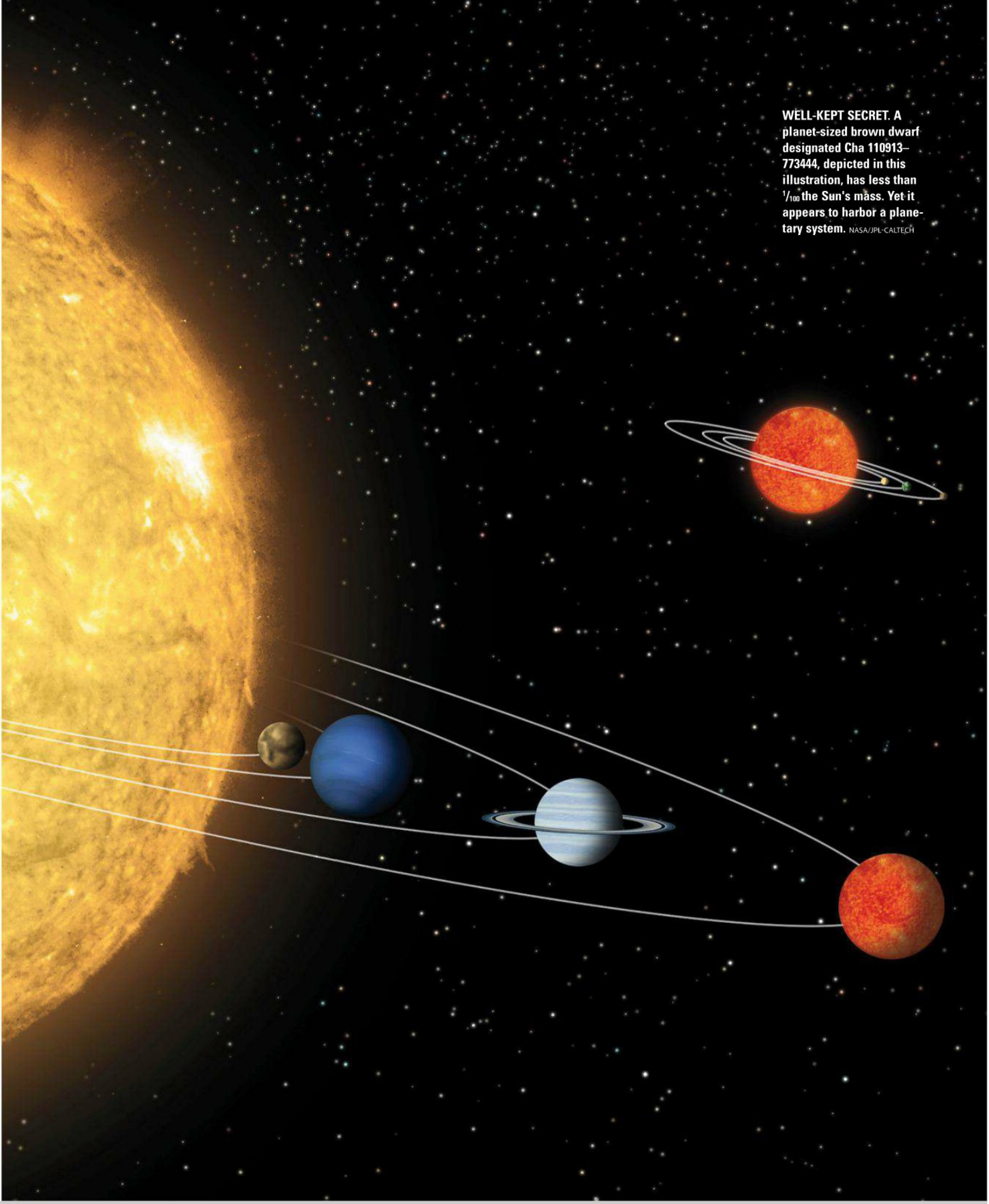
The population of brown dwarfs ballooned. In 2005, based on surveys using the Hubble Space Telescope, astronomers at Arizona State University estimated our galaxy may hold as many brown dwarfs as all other types of stars — 100 billion.


NASA/S. KULKARNI/D. GOLIMOWSKI

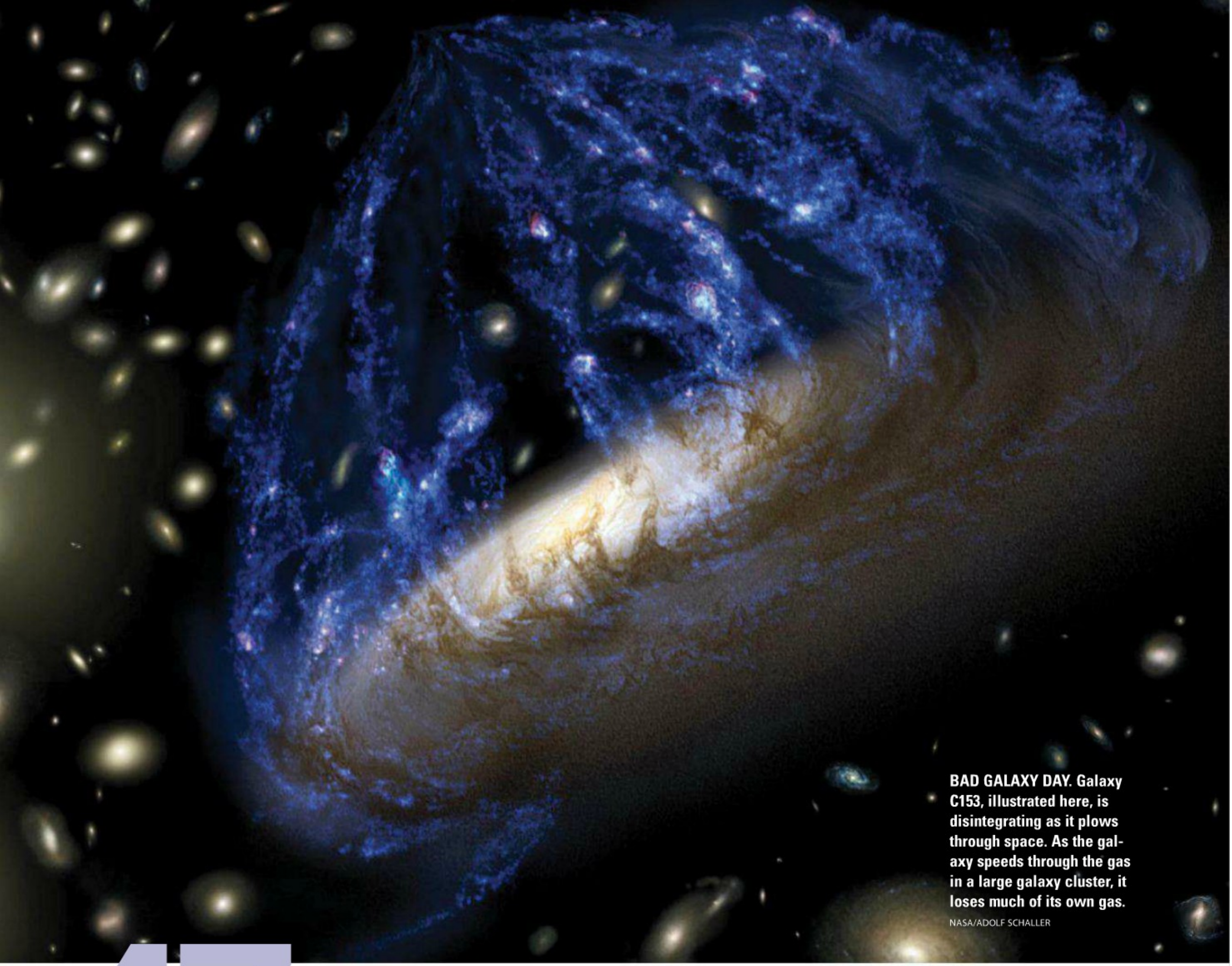
BROWN DWARF #1. **In 1995, astronomers discovered their first brown dwarf, called Gliese 229B, a small companion to the cool, red star Gliese 229, located 19 light-years from Earth in the constellation Lepus.**


NASA/STScI

COSMIC SNACK. **As many as 100 million Sun-like stars in the Milky Way harbor close-orbiting Jupiter-like planets or stillborn stars like brown dwarfs. These close companions may eventually be destroyed by their parent stars.**



WELL-KEPT SECRET. A planet-sized brown dwarf designated Cha 110913–773444, depicted in this illustration, has less than $^1/_{100}$ the Sun's mass. Yet it appears to harbor a planetary system. NASA/JPL-CALTECH



BAD GALAXY DAY. Galaxy C153, illustrated here, is disintegrating as it plows through space. As the galaxy speeds through the gas in a large galaxy cluster, it loses much of its own gas.

NASA/ADOLF SCHALLER

47

What **happens** at the **cores** of **galaxy clusters**?

The centers of rich clusters of galaxies contain the densest concentrations of matter in the universe. They're also among the most violent places we know of. As time rolls on and large galaxies swarm around meeker ones, mergers take place. Big galaxies grow larger by eating small ones. As this happens, worlds are torn apart, stars shredded, and gas clouds compressed into reckless new throes of star formation. We live in a relatively quiet corner of the Milky Way Galaxy. By contrast, the centers of rich galaxy clusters are the universe's most chaotic locations, constantly bustling with activity.

Until recently, astronomers thought they understood how galaxy clusters form. As matter collapses inward, pulled by gravity, groups of galaxies and clumps of matter crush together. The monsters of the scene, the big galaxies, fall toward the center, where the most mass resides.

Hot gas in the cluster core loses energy and cools by emitting X rays. As the gas inside the cluster cools, it also contracts.

NASA/ESA/ACS SCIENCE TEAM

LOGJAM. **The center of galaxy cluster Abell 1689 appears chaotic thanks to a dense thicket of stars and dust shed by its multitude of whirling galaxies.**

Astronomers dubbed this contracting gas a cooling flow. Up until 2006, the idea had been gospel since first proposed in 1977.

But galaxy clusters have thrown astronomers a few surprises. One of the theorists who came up with the cooling-flow model, Paul Nulsen of the Harvard-Smithsonian Center for Astrophysics, says, "We now think it's almost completely wrong." Researchers are now focusing on a model where more complex flows drive the formation and evolution of galaxy clusters.

But gas cooling remains an important feature of the latest models. The trouble is, astronomers just don't know what's heating the gas. X-ray observations suggest that a vast amount of cool gas should be produced in the cores of galaxy clusters each year. This should lead to massive episodes of star formation. "But when we measured rates of star formation," says Brian McNamara of Ohio State University, "we were getting 10 to 20 solar-masses a year or less."

So, what could be hiding in the cool gas? Several years ago, McNamara uncovered a clue in the distant galaxy cluster Hydra A, some 840 million light-years away. Using NASA's Chandra X-ray Observatory, he showed that powerful jets heated the surrounding gas.

In 2005, McNamara and a group of collaborators again used Chandra, this time to image X-ray emission from a very distant cluster, MS 0735.6+7421, which lies 2.6 billion light-years away in Camelopardalis.

McNamara and his team found two gigantic cavities within the cluster. Each of these voids was roomy enough to house 600 Milky Ways. The cavities were expanding away from a supermassive black hole. The team calculated that the energy required to displace this gas was some 10^{61} ergs — equivalent to the energy released by 10 billion supernovae. This was the largest single eruption astronomers have ever recorded.

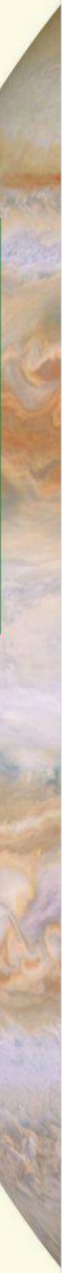
So, it appears the mysterious heat source inside galaxy clusters are jets from active galaxies powered by supermassive black holes. But the mystery lingers — jet luminosities don't exactly match the clusters' X-ray cooling rates. So, while the whole picture of galaxy-cluster heating and cooling is becoming clearer, it's a long way from being solved.

What astronomers *do* know is that massive galaxy clusters remain among the cosmos' most energetic spots.

GRAVITATIONAL WALTZ. **Engaging in a dance of destruction, galaxies in the group called Seyfert's Sextet flirt with mergers.** NASA/J. ENGLISH, S. HUNSBERGER, S. ZONAK, J. CHAARLTON, S. GALLAGHER, AND L. FRATTARE

48

Is Jupiter a failed star?



The brilliant planet Jupiter dazzles anyone with a clear sky. Roman observers named Jupiter after the patron deity of the Roman state following Greek mythology, which associated it with the supreme god, Zeus. But when Galileo turned his telescope skyward in 1610, Jupiter took on new significance. Galileo discovered the planet's four principal moons — and witnessed the first clear observation of celestial motions centered on a body other than Earth.

Astronomers recognized Jupiter as the largest planet in the solar system long before any spacecraft provided detailed exploration. The planet's mammoth size — 88,846 miles (142,984 kilometers) at the equator — holds 2.5 times the mass of all the other planets combined. This makes Jupiter the most dominant body in the solar system after the Sun. The planet's volume is so great that 1,321 Earths could fit inside it.

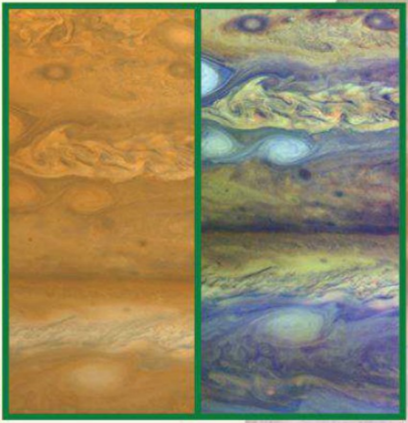
Jupiter is a magnificent example of a gas-giant planet. It has no solid surface and is composed of a small rocky core enclosed in a shell of metallic hydrogen, which is surrounded by liquid hydrogen, which, in turn, is blanketed by hydrogen gas. By count of atoms, the atmosphere is about 90-percent hydrogen and 10-percent helium.

Jupiter's dominance of the solar system has led to many spacecraft missions, beginning with Pioneer 10's 1973 flyby. A year later, Pioneer 11 passed the great planet. But sophisticated, close-up study of the giant planet began with the twin flybys of NASA's Voyagers in 1979.

Voyager 1 and 2 increased our jovian knowledge immensely. They mapped the planet's moons, took detailed images of the Jupiter's complex atmosphere, and even discovered a faint set of rings.

NASA's Galileo mission, which entered jovian orbit in 1995, gave scientists another windfall. Even as it approached Jupiter in 1994, Galileo witnessed one of the greatest events in solar system history — Comet Shoemaker-Levy 9's spectacular crash into the giant planet. Galileo sent a probe plummeting into Jupiter's atmosphere. The probe sampled the atmosphere directly and returned much information before immense pressure deep below Jupiter's clouds crushed it. In 2003, at mission end, Galileo itself met the same fate.

Jupiter's size and compositional similarity to brown dwarfs and small stars have led some to label it a "failed star." Had the planet formed with more mass, they claim, Jupiter would have ignited nuclear fusion and the solar system would have been a double-star system. Life might never have evolved on Earth because the temperature would have been too high and its atmospheric characteristics all wrong.



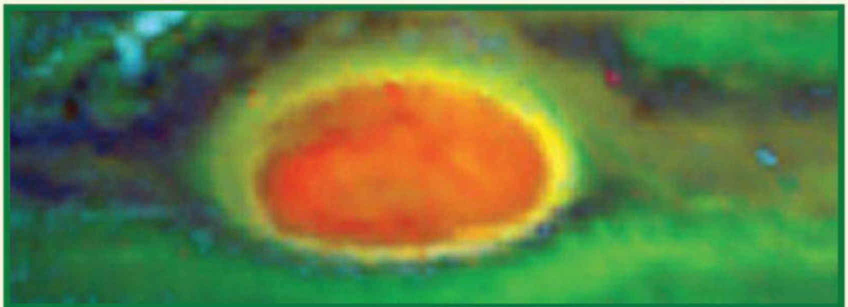
NASA/JPL

▲ **JOVIAN TURBULENCE. True-color (left) and false-color mosaics show how eastward and westward bands of air between the planet's equator and polar regions control Jupiter's atmosphere.**

But although Jupiter is large as planets go, it would need to be about 75 times its current mass to ignite nuclear fusion in its core and become a star. Astronomers have found other stars orbited by planets with masses far greater than Jupiter's.

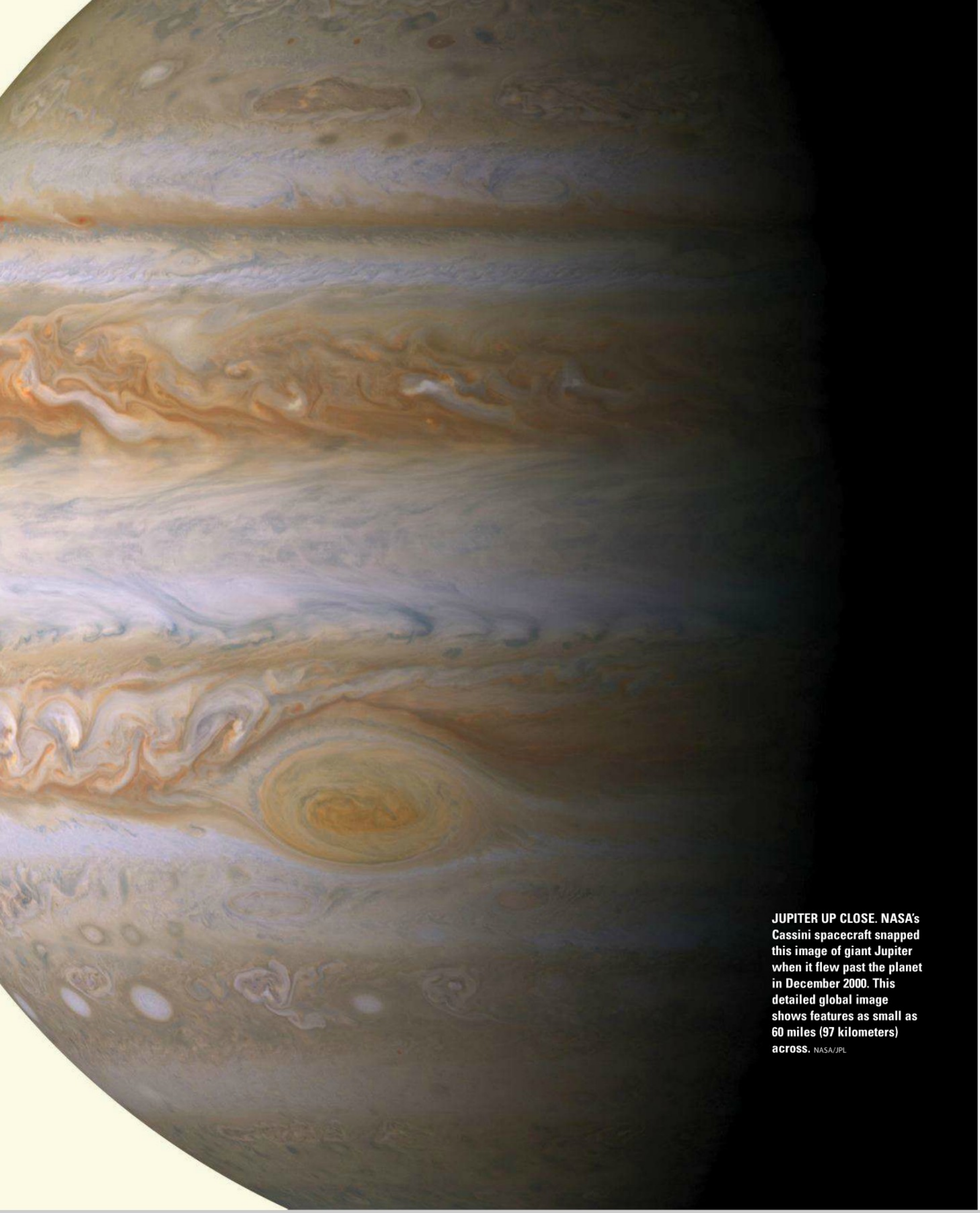
What about sub-stellar brown dwarfs? Our largest planet still doesn't come close to these "almost stars." Astronomers define brown dwarfs as bodies with at least 13 times Jupiter's mass. At this point, a hydrogen isotope called deuterium can undergo fusion early in a brown dwarf's life.

So, while Jupiter is a planetary giant, its mass falls far short of the mark for considering it a failed star.



GREAT STORM. NASA's Galileo spacecraft spotted an unusual ammonia-ice cloud (light blue) above and to the left of Jupiter's long-lasting Great Red Spot (center) in this false-color image.

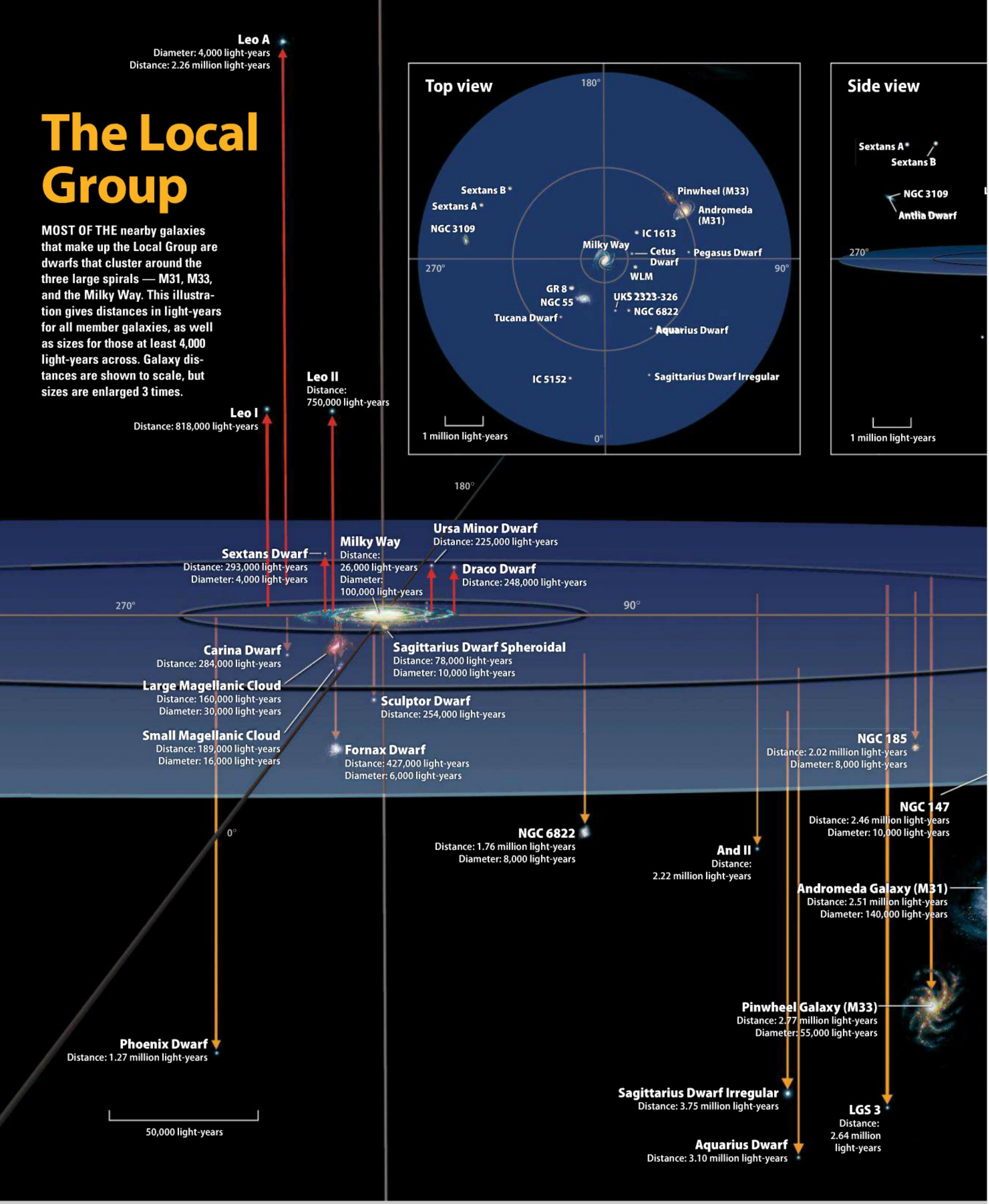
NASA/JPL

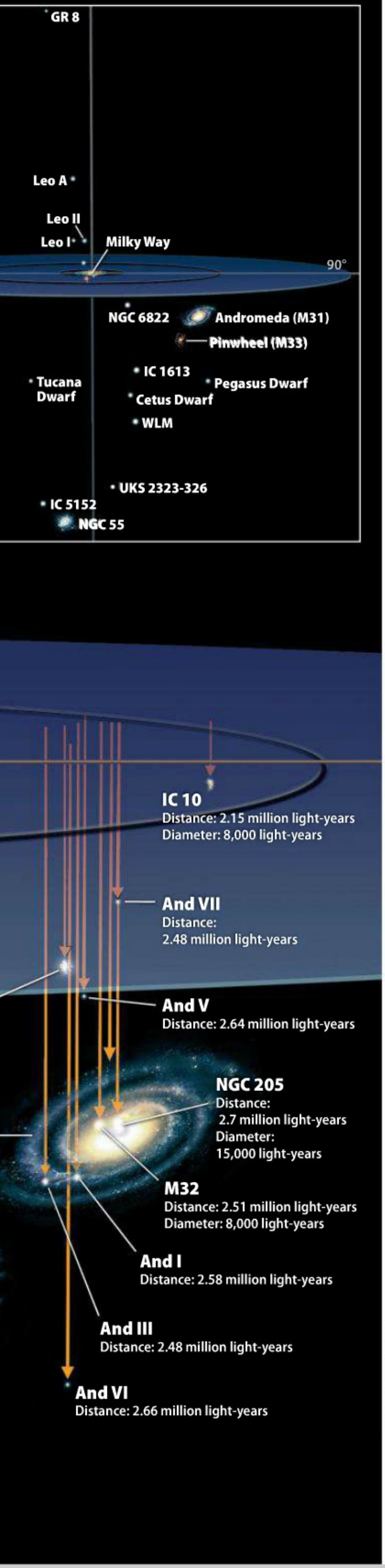


JUPITER UP CLOSE. NASA's Cassini spacecraft snapped this image of giant Jupiter when it flew past the planet in December 2000. This detailed global image shows features as small as 60 miles (97 kilometers) across. NASA/JPL

The Local Group

MOST OF THE nearby galaxies that make up the Local Group are dwarfs that cluster around the three large spirals — M31, M33, and the Milky Way. This illustration gives distances in light-years for all member galaxies, as well as sizes for those at least 4,000 light-years across. Galaxy distances are shown to scale, but sizes are enlarged 3 times.


Leo A
Diameter: 4,000 light-years
Distance: 2.26 million light-years
Top view
180°
270°
90°
0°
Sextans B
Sextans A
NGC 3109
Pinwheel (M33)
Andromeda (M31)
IC 1613
Milky Way
Cetus Dwarf
Pegasus Dwarf
WLM
GR 8
NGC 55
UKS 2323-326
NGC 6822
Tucana Dwarf
Aquarius Dwarf
IC 5152
Sagittarius Dwarf Irregular
1 million light-years
Side view
Sextans A
Sextans B
NGC 3109
Antlia Dwarf
270°
1 million light-years
Leo II
Distance: 750,000 light-years
Leo I
Distance: 818,000 light-years
180°
Ursa Minor Dwarf
Distance: 225,000 light-years
Milky Way
Distance: 26,000 light-years
Diameter: 100,000 light-years
Sextans Dwarf
Distance: 293,000 light-years
Diameter: 4,000 light-years
Draco Dwarf
Distance: 248,000 light-years
270°
90°
Carina Dwarf
Distance: 284,000 light-years
Sagittarius Dwarf Spheroidal
Distance: 78,000 light-years
Diameter: 10,000 light-years
Large Magellanic Cloud
Distance: 160,000 light-years
Diameter: 30,000 light-years
Sculptor Dwarf
Distance: 254,000 light-years
Small Magellanic Cloud
Distance: 189,000 light-years
Diameter: 16,000 light-years
Fornax Dwarf
Distance: 427,000 light-years
Diameter: 6,000 light-years
NGC 185
Distance: 2.02 million light-years
Diameter: 8,000 light-years
NGC 147
Distance: 2.46 million light-years
Diameter: 10,000 light-years
0°
NGC 6822
Distance: 1.76 million light-years
Diameter: 8,000 light-years
And II
Distance: 2.22 million light-years
Andromeda Galaxy (M31)
Distance: 2.51 million light-years
Diameter: 140,000 light-years
Pinwheel Galaxy (M33)
Distance: 2.77 million light-years
Diameter: 55,000 light-years
Phoenix Dwarf
Distance: 1.27 million light-years
Sagittarius Dwarf Irregular
Distance: 3.75 million light-years
LGS 3
Distance: 2.64 million light-years
Aquarius Dwarf
Distance: 3.10 million light-years
50,000 light-years


GR 8
Leo A
Leo II
Leo I
Milky Way
90°
NGC 6822
Andromeda (M31)
Pinwheel (M33)
Tucana Dwarf
IC 1613
Pegasus Dwarf
Cetus Dwarf
WLM
UKS 2323-326
IC 5152
NGC 55
IC 10
Distance: 2.15 million light-years
Diameter: 8,000 light-years
And VII
Distance:
2.48 million light-years
And V
Distance: 2.64 million light-years
NGC 205
Distance:
2.7 million light-years
Diameter:
15,000 light-years
M32
Distance: 2.51 million light-years
Diameter: 8,000 light-years
And I
Distance: 2.58 million light-years
And III
Distance: 2.48 million light-years
And VI
Distance: 2.66 million light-years

ASTRONOMY: ROEN KELLY

49

How many **galaxies** are in our **Local Group**?

Our Milky Way Galaxy wheels within the Local Group of Galaxies in a relatively quiet corner of the cosmos. The Virgo cluster of galaxies, some 50 million light-years away, plays city center to our boondocks. The Virgo cluster holds an amazing 2,000 "island universes." Our little Local Group, by contrast, contains roughly three dozen galaxies, most of them unimpressive dwarfs.

Many, perhaps most, galaxies exist in such small groups scattered throughout the cosmos. The Local Group spans a mere 6 million light-years, and only three large galaxies lie within it. The most significant, the Andromeda Galaxy (M31), is an expansive spiral whose magnificent disk extends 140,000 light-years. Next in size is our own Milky Way, with a disk spanning 100,000 light-years. The third spiral in the group, M33 (sometimes called the Pinwheel Galaxy), measures 55,000 light-years across.

Three big galaxies and dozens of small ones form the Local Group.

The Local Group's remaining members include irregular, elliptical, and dwarf elliptical galaxies, most of which are quite small. The two big guys on the block, Andromeda and the Milky Way, each have a retinue of satellite galaxies around them. Andromeda hosts ellipticals M32, NGC 205, NGC 147, and NGC 185, and dwarfs Andromeda I, II, III, V, VI, and VII.

The Milky Way holds the Large and Small Magellanic Clouds, both irregulars, plus many dwarf galaxies. Prominent ones lie in Carina, Draco, Fornax, Sagittarius, Sculptor, Sextans, and Ursa Minor.

The 40 or so galaxies of the Local Group originated about 13 billion years ago, when the first clumps of matter accreted into protogalaxies. As these clumps compressed, stars formed and ignited their nuclear-fusion fires. When the first stars and clusters emerged from the billion-year-long Dark Ages that followed the Big Bang, the Local Group stretched only 600,000 light-years across. Being so close together, galaxies merged more often back then. Such mergers may have built the Milky Way out of as many as 100 protogalaxies.

This process continues: Our galaxy is in the process of shredding and devouring the Sagittarius Dwarf Spheroidal Galaxy, and it eventually will absorb the Magellanic Clouds. Several billion years from now, the Andromeda Galaxy and the Milky Way will collide in a clash of fireworks that ultimately will create a single, messy super-spiral.

Observing the Local Group's galaxies gives astronomers a microcosm — a laboratory close at hand that represents the universe at large. A substance astronomers call dark matter accounts for ⅕ of the universe's mass-energy, but, as yet, no one knows what the stuff is. Using a technique called gravitational lensing, astronomers have scoured the Milky Way's halo and ruled out several suspected candidates.

Likewise, astronomers also use the nearest galaxies to study where black holes form. What they've found in our galactic neighborhood matches up well with observations in more distant galaxies.

50 Do **neutrinos** hold **secrets** to the **cosmos?**

For a quarter of a century, Wolfgang Pauli's prediction remained an educated guess. In 1930, the Austrian physicist predicted the existence of a ghostly new subatomic particle.

After observing beta decay in a radioactive nucleus, Pauli noted that an undiscovered particle must exist to explain the resulting spectrum. During beta decay, a proton becomes a neutron by emitting a positron. But Pauli argued the nucleus also emitted an unknown electrically neutral particle. He thought this hypothetical particle had less than 1 percent of a proton's mass.

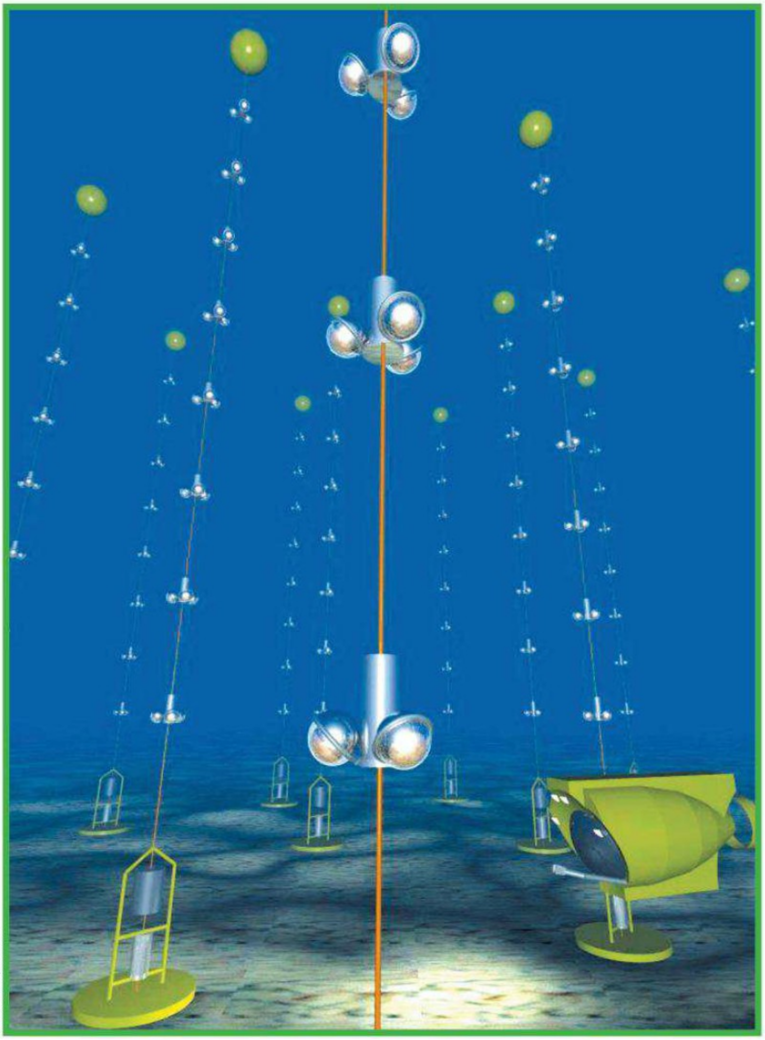
During the 1930s, Italian physicist Enrico Fermi investigated the problem and completed the work Pauli began. Fermi thought the weak nuclear force destabilized atomic nuclei and caused particle transformations. He called Pauli's ghostly particle the neutrino, Italian for "little neutral one."

German physicist Hans Bethe, meanwhile, was attacking the question of how stars shine. While investigating this question, Bethe realized that neutrinos played a key role. Fusion reactions in the Sun's core create a torrent of neutrinos, a fraction of which passes through Earth 8 minutes later. These evanescent particles carry with them a record of what happens inside a star.

Neutrinos come in three types — electron, muon, and tau. But these elusive particles don't interact much with other matter. Neutrinos can pass almost unfettered through us, Earth, the Sun, or the superdense heart of an exploding star. While they exist in tremendous numbers, the challenge of neutrinos is detecting them.

In the 1950s, physicists Fred Reines and Clyde Cowan began a series of experiments to try. By the mid-1950s, their Project Poltergeist showed that it could be done. Their experiment picked up neutrinos by using a nuclear reactor as a source and a water tank as a detector, both sunk deep in a mine.

Although Bethe outlined the processes by which stars obtain energy through



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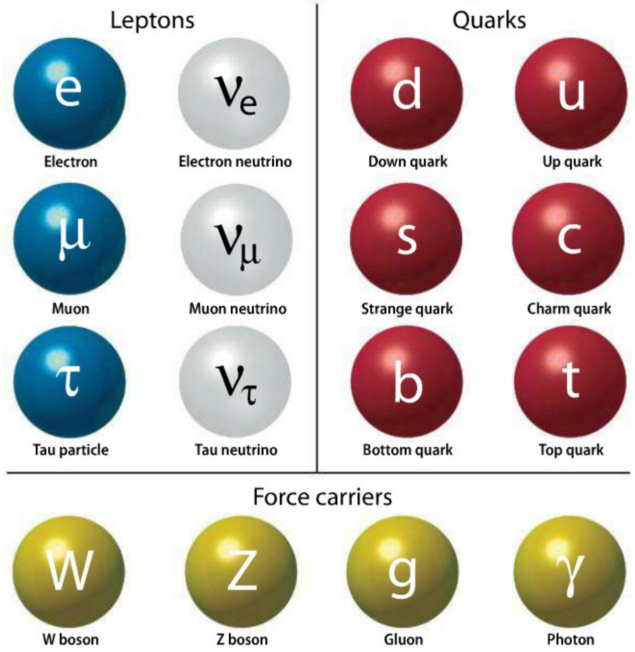
BOTTOM LINES. Like strands of high-tech kelp, the Antares detector array rises from the seafloor off Marseille, France. Precisely timing a neutrino's light flash is the key for tracking a particle's path through the array.

Matter's fundamentals: The particle zoo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Tau neutrino
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Bottom quark
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W
W boson
Z
Z boson
g
Gluon
γ
Photon

COSMIC BASICS. Normal matter comprises electrons and neutrinos, plus particles built from combinations of three quarks, like protons and neutrons. Exchanging force-carrying entities, like photons and gluons, gives rise to electromagnetism and nuclear forces.

ASTRONOMY: ROEN KELLY

hydrogen fusion, many neutrino mysteries remain. For a long time, astronomers have known the universe contains much more matter than the bright stuff we can see. They know this because they track galaxies moving in response to the gravitational pull of large amounts of material that neither emits nor blocks light — dark matter.

Could untold varieties of neutrinos account for much — or even all — of the dark matter astronomers believe is out there? According to physicist John Learned of the University of Hawaii, the answer is yes.

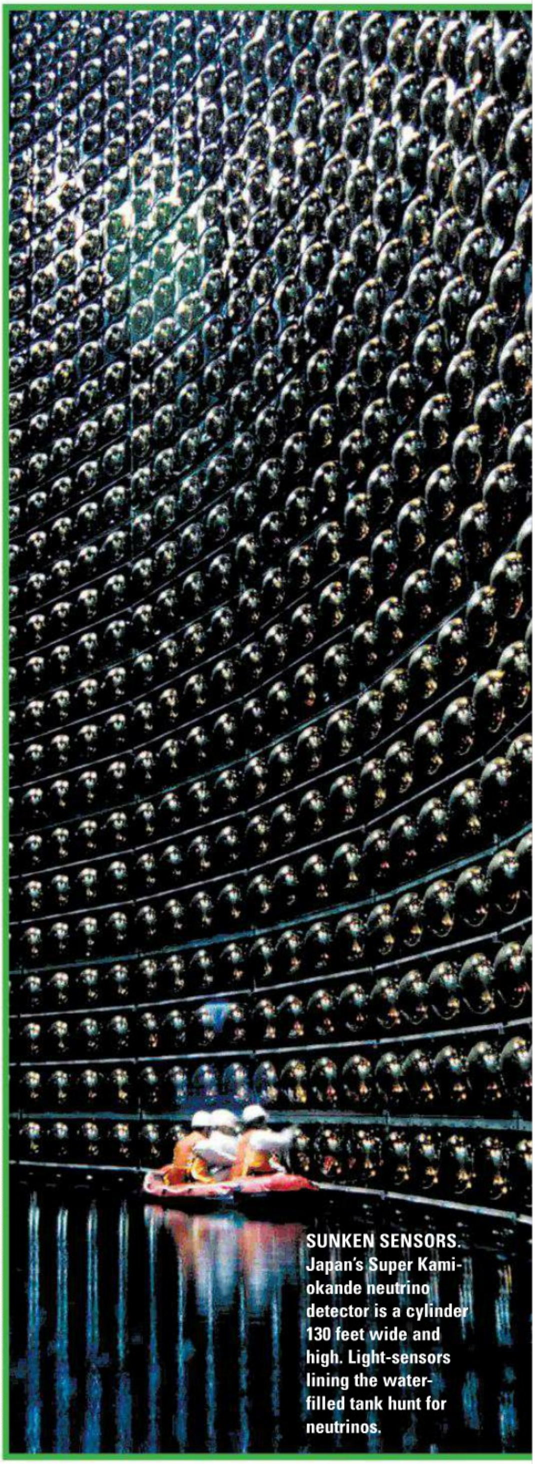
"We now know that neutrinos constitute about as much mass as all the stars one sees in the night sky," Learned says. "It could be a lot more. Cosmologists need to take neutrinos into account."

Could untold types of neutrinos account for dark matter?

Independent of neutrinos' possible role as dark matter, the hard-to-catch particles may also help astronomers decipher how matter itself came to be. When the Big Bang occurred, matter and antimatter should have been created in equal amounts. And when matter and antimatter meet, they annihilate each other. If the amounts had been equal, then only radiation would have filled the universe.

Why is there so much matter in the cosmos? Maybe neutrinos played a key role in the universe's early asymmetry. If so, we owe our existence to them.

Neutrinos surface in other cosmic mysteries. Expect to hear a lot more about these strange particles as scientists continue to probe matter's secrets. SO



SUNKEN SENSORS. Japan's Super Kamiokande neutrino detector is a cylinder 130 feet wide and high. Light-sensors lining the water-filled tank hunt for neutrinos.

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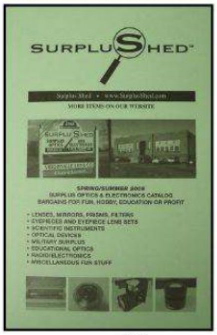

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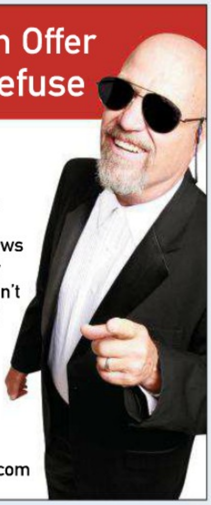

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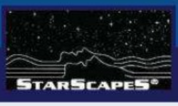

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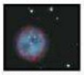

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